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SUMMARY OF SHORT-PERIOD EXPLOSION AND EARTHQUAKE CODA SHAPES WITH IMPLICATIONS FOR REGIONAL DISCRIMINATION

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26 September 1977

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This report presents a collection of small and large earthquake short-period coda shapes as a function of distance. It is summarized from previous studies by Cohen, Sweetser, and others. New results include coda shapes for $\Delta < 20°$. The report is intended to serve as a reference for workers who investigate problems related to hiding an explosion in an earthquake. A detailed examination of earthquake and explosion coda also shows for $\Delta < 20°$ that the amplitude ratio P_g/L_g serves as a discriminant in the Southwest United States.

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ABSTRACT

This report presents a collection of small and large earthquake short-period coda shapes as a function of distance. It is summarized from previous studies by Cohen, Sweetser, and others. New results include coda shapes for $\Delta < 20°$. The report is intended to serve as a reference for workers who investigate problems related to hiding an explosion in an earthquake. A detailed examination of earthquake and explosion coda also shows for $\Delta < 20°$ that the amplitude ratio P_g/L_g serves as a discriminant in the Southwest United States.

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INTRODUCTION

This report is intended to summarize the results of coda studies that focus on the hide-in-earth (HIE) technique. Ideally, it will be a convenient reference for future investigators in the HIE field. The Seismic Data Analysis Center (SDAC) has performed substantial research on the subject of evasion of seismic detection and discrimination by the hide-in-earthquake (HIE) technique. Using this technique, evaders would first wait for a large earthquake to occur and then detonate the explosion, hoping that the coda of the earthquake would hide the explosion signals. Blandford, Cohen and Husted (1971), Fink, Miamidian and Myers (1971), Lukasik (1971), as well as others, have all examined or discussed the HIE technique.

Each of these investigators needed to estimate the coda shapes of candidate hiding earthquakes. Beginning in 1972 Cohen, and co-workers, embarked on a comprehensive set of coda measurement and tabulation (Cohen and Sweetser and Dutterer (1972), Sweetser, Cohen and Tillman (1973), Cohen and Sweetser (1973),

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Blandford, R.R., T.J. Cohen and H.L. Husted (1971), Opportunities for foreign nations to hide an underground nuclear test in an earthquake (U) CLASSIFIED Seismic Data Laboratory Report No. 283, Teledyne Geotech, Alexandria, Virginia.

Fink, D.R., L.R. Miamidian and W. Myers (1971), Seismic network studies (U) CLASSIFIED, LOG GAC 7157, General Atronics, Magnavox, Philadelphia, Pennsylvania.

Lukasik, S. (1971), In "Hearings on status of current technology to identify seismic events as natural or man-made", before the Joint Committee on Atomic Energy of the Congress of the United States, October 1971. GPO No. 69-648.

Cohen, Sweetser and Dutterer (1972), P and PKP coda decay characteristics for earthquakes, Seismic Data Laboratory Report No. 301, Teledyne Geotech, Alexandria, Virginia.

Sweetser, E.I., T.J. Cohen and M.F. Tillman (1973), Average P and PKP codas for earthquakes, Seismic Data Laboratory Report No. 305, Teledyne Geotech, Alexandria, Virginia.

Cohen, T.J. and E.I. Sweetser (1973), False alarm probabilities for mixed events, SDAC-TR-73-8, Teledyne Geotech, Alexandria, Virginia.

Sweetser and Cohen (1973), and Sweetser and Cohen (1974).) Sweetser and Cohen (1974b) showed that large earthquakes have coda shapes more extended in time than small ones; this demonstration was consistent with the hypothesis that large events are made up of many smaller ones. Blandford and Sweetser (1975) showed that coda shapes are similar whether measurements are made on the LRSM or WWSSN short-period systems and that coda levels are consistently high at some stations by 0.1-0.2 magnitude units. They also demonstrated that reverberation between successive coda maxima is less at stations overlying a low-Q mantle than at those overlying a high-Q mantle by 0.1 m_b unit. Furthermore, they showed that for times greater than one or two minutes into the coda, minimal coda levels are typically 0.3 magnitude units less than the maxima.

Blandford and Clark (1974) showed that, although occasional exceptions appear, earthquake coda from each of three selected regions of Kamchatka had its own characteristic coda shape.

Sweetser, E.I. and T.J. Cohen (1973), Average P and PKP codas for earthquakes (103-118°), SDAC-73-10,Teledyne Geotech, Alexandria, Virginia.

Sweetser, E.I. and T.J. Cohen (1974), Average P and PKP codas for earthquakes (118-180°), SDAC-TR-74-19, Teledyne Geotech, Alexandria, Virginia.

Sweetser, E.I. and T.J. Cohen (1974b), Evidence consistent with a multiple-event mechanism for large earthquakes, Geophys. Res. Lett., v. 1, p. 363-365.

Blandford, R.R. and E.I. Sweetser (1975), Short-period earthquake coda shape as a function of geology and system response, SDAC-TR-75-10, Teledyne Geotech, Alexandria, Virginia.

Blandford, R.R. and D. Clark (1974), Variability of seismic wave-forms at LASA from small subregions of Kamchatka, SDAC-TR-75-12, Teledyne Geotech, Alexandria, Virginia.

PROCEDURES

The only new work undertaken for this study was that required to adequately characterize codas at distances less than 20°. Close-in coda are crucial to simulations which assume that detection stations may be allowed in the seismic regions of possible evading nations. Previous studies by Cohen and co-workers made only three measurements in the distance range 0-5°, and in the distance range out to 20° Cohen's data was so sparse that regions of similar coda type could not be confidently defined.

In this report two data sources were selected for the close-in coda. The seismograms in the LRSM shot reports for Nevada Test Site (NTS) explosions were useful because the gains were adjusted suitably before each shot. This data set comprises a single-source to many-station set of data.

Data from earthquakes throughout the Southwest United States, and in Mexico, can be measured at the Tonto Forest Observatory (TFO) near Payson, Arizona. This situation exists because traces at many different gains were recorded on film during the operation of that station, thus yielding a many-source to single-station data set.

The authors of this report did much to ensure that the sample population for close-in coda was as representative and unbiased as possible. The sampling technique for the TFO earthquake coda is perhaps the most satisfactory. In each distance range, one event was taken from each Flinn-Engdahl geographic region that had a measurable event in that distance range between the years 1962-1973.

The explosion codas from the distance ranges listed in Table I provided the basis for selecting the distance ranges used in the sample. In Table I the distance intervals are expressed in fractional degrees because the original sorting of the explosion coda was on the basis of 100-kilometer intervals. The authors attempted to have the explosion coda well distributed within each distance range and with as much variation in recording station as possible, and they tried to obtain approximately ten observations in each distance range, if possible.

The method of coda measurement shown in Figure 1 was the same as discussed in the already mentioned papers by Cohen and co-workers. The mean explosion

TABLE I
Local and Regional Coda Data

Distance Range	Number of Eq.	Explosions	Stations
0- 1.8°	4	BOXCAR	MN-NV
		CLEARWATER	CU-NV
		CHINCHILLA	DV-CL
		FAULTLESS	MN-NV
		FORE	CU-NV
1.8- 2.7°		AUK	EK-NV, SG-AZ
		BOURBON	MN-NV
		CLEARWATER	MN-NV
		BUFF	KN-UT
		CHARTREUSE	MN-NV
		CHINCHILLA	AT-NV
	↑	CORDUROY	MN-NV
	2	DILUTED WATERS	MN-NV
	↓	FORE	KM-CL
2.7- 3.6°		CLEARWATER	KN-UT
		CHINCHILLA	WM-AZ
		CUP	SG-AZ
		FAULTLESS	KN-UT
		GREELEY	KN-UT
		HALFBEAK	KN-UT
		HARDHAT	WM-AZ

TABLE I (Continued)

Distance Range	Number of Eq.	Explosions	Stations
3.6- 4.5°		AARDVARK	TF-CL
		CLEARWATER	CP-CL, MV-CL
		CHINCHILLA	FM-UT, FS-AZ, CP-CL
		CUP	JR-AZ
		DILUTED WATERS	LG-AZ
		FISHER	CP CL
4.5- 5.4°	↑	ANTLER	FS-AZ
	22	AUK	HR-AZ
	↓	BOXCAR	CP-CL
		BRONZE	SN-AZ
		BUFF	TFO
		CHINCHILLA	SF-AZ
		CUP	LG-AZ, WO-AZ
		FISHER	MN-CL
		FORE	BX-UT
		HARDHAT	SF-AZ
5.4-6.3°	11	AARDVARK	VN-UT
		BOURBON	MO-IO, UBO
		CLEARWATER	BX-UT, UBO
		CUP	GE-AZ, UBO
		GREELEY	MO-ID, UBO
6.3- 7.1°	7	CLEARWATER	HL-ID, DR-CO
		BRONZE	HL-ID
		CHINCHILLA	VT-OR, DR-CO, HL-ID
		FISHER	SV-AZ, ML-NM
		HARDHAT	ML-NM

TABLE I (Continued)

Distance Range	Number of Eq.	Explosions	Stations
7.1- 8.9°	9	CLEARWATER	TD-NM, BMO
		DILUTED WATERS	LC-NM, BMO
		HARDHAT	PT-OR
		BOBAC	PT-OR, BMO
8.9-10.7°	12	AARDVARK	PM-WY
		BOXCAR	LC-NM
		CLEARWATER	RT-NM
		BRONZE	LC-NM
		COMMODORE	FK-CO
		FAULTLESS	LC-NM
		HARDHAT	ED-TX
10.7-12.5°		BILBY	TK-WA
		CLEARWATER	FR-MA
		BUFF	HV-MA, SW-MA
		CHARTREUSE	RG-SD
		CORDUROY	RG-SD
		FORE	FR-MA, AZ-TX, TK-WA
		HARDHAT	EF-TX, GN-NM, BM-TX
12.5-14.3°	11	BUFF	WN-SD, WMO
		CHARTREUSE	WN-SD, WMO
		CLEARWATER	GI-MA, WMO
		CUP	FO-TX, WMO
		FORE	SK-TX, GI-MA, WMO
		HARDHAT	SS-TX, WMO

TABLE I (Continued)

Distance Range	Number of Eq.	Explosions	Stations
14.3-17.7°		AARDVARK	TO-OK
		BILBY	GV-TX
		BRONZE	AP-OK, GV-TX
		BUFF	CR-NB
		CLEARWATER	AP-OK, RY-ND
		DUMONT	JP-AT
		FAULTLESS	PG-BC
		HALFBEAK	JP-AT
		HARDHAT	LP-TX
17.7-21.0°	11	AARDVARK	SJ-TX, SE-MN
		BUFF	KC-MO, PG-BC
		CHARTREUSE	KC-MO, PG-BC
		CLEARWATER	DU-OK, HH-ND
		FORE	HH-ND, HE-TX

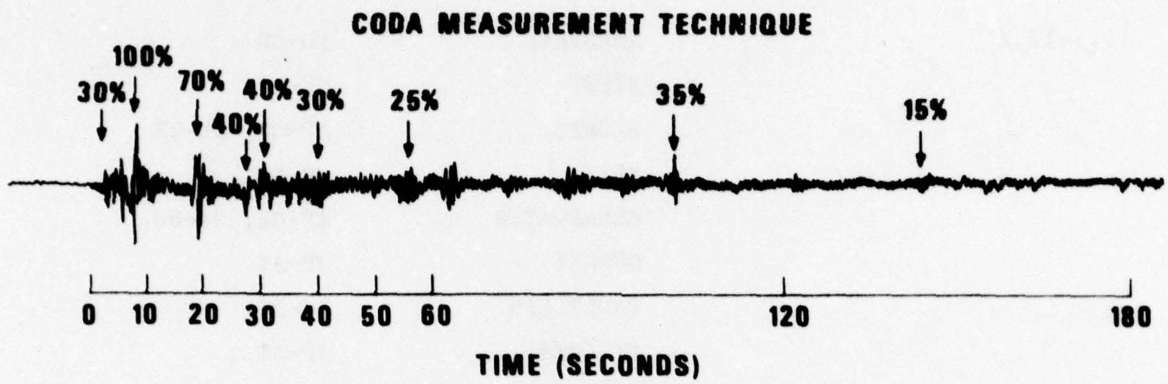

Figure 1. The analyst selects the maximum signal amplitude in the time intervals indicated. He requires that the dominant frequency be in the range greater than 0.5 Hz. In each time interval, for a suite of coda measurements, the average and standard deviation of the logarithm to the base 10 of the percentages is calculated. The result is a mean coda shape, together with its standard deviation expressed in magnitude units.

coda shapes from adjacent distance intervals were examined and where, considering the standard deviation of the data points, qualitative evidence suggested that the hypothesis that the two coda means were identical could not be rejected, the data were merged, thus leaving a total of nine distinct distance ranges. Then one earthquake was measured at TFO from each of the Flinn-Engdahl geographic regions which fell within each of the nine distance ranges. Table I shows how many earthquakes this procedure yielded for each distance range.

RESULTS

All events analyzed for regional coda shapes had m_b values less than 5.8. Thus, they are classified as "small" events in the nomenclature of Cohen and co-workers. These workers defined a "large" event as one with NEIS m_b or M_s $\geq$ 7.0. Such events generally clip WWSSN systems at distances less than 20°. No "large" events occured within 20° of TFO during its operational period. As an estimate for large coda shapes in this distance range see Sweetser and Cohen (1974b), who generalized from teleseismic observations that normalized coda levels for large events are retarded in their decay curve by one or two minutes.

Appendix I, pages A1 through A10, give average coda shape estimates for small events. The data up to 21° has been gathered for this report. The remainder comes from the appropriate graphs in the work of Cohen and co-workers. The average curves are extended out to the last data point in time at which more than half, N/2, of the coda have measured values. (In a few cases the average was carried out to points for which the number of coda was N/2-1). Of the individual coda between 0 and 8.9°, four showed an exceptionally good signal-to-noise ratio out to 8 minutes, and followed the mean patterns as their amplitude decreased. No reason exists to suspect that they were abnormal in the slope of their amplitude decay. They seem to be simply large, well-recorded events. The average slope of these coda in the time interval 4-8 minutes was 0.42 magnitude unit per minute. This average was chosen as the asymptotic slope for all of the average coda in the distance ranges between 0°-8.9°.

For the two distance ranges 8.9-10.7°, 10.7-14.3° evidence exists from the individual coda plotted that 0.42 magnitude units per minute was not a satisfactory asymptotic slope. On the other hand, there was no truly satisfactory coda of long duration upon which to base the asymptotic coda slope. Therefore, the slope between the last two average coda points, which are determined from averages of more than one-half the set, was extrapolated to larger times. This results in slopes of 0.3 and 0.15 magnitude units per minute respectively.

Examination of large events recorded at all distances greater than 21° revealed no tendency for the asymptotic codas to have different decay rates.

Thus, by trial and error, a slope of 0.034 magnitude units per minute was selected and compared visually to the long-time coda in each of the other distance ranges. The hypothesis that this slope was a correct mean value for each distance range could not be rejected, so it has been used for the asymptotic coda slope for all coda with $\Delta > 21°$. Note that if we assume this decay to be due strictly to absorption, $A \sim \exp(-\omega t/2Q)$ at 1 Hz, then $Q \simeq 2400$. Of course, some of the amplitude decay is due to divergence losses, multiple reflections, etc., so that this Q is probably a lower limit, and, since many of the later phases are composed of shear waves over part of their life, the situation is even more complicated.

Along with the mean coda plots in the distance ranges 5-21° we have plotted the appropriate mean codas from the previous study of Sweetser, et al. (1973). In general, coda from the earlier studies show a lesser decay with time than those coda determined in this study. For $\Delta < 10°$ most of the difference is probably because (to be discussed below) our average codas contain explosions which decay more rapidly in this distance range. However, the difference persists for $10 < \Delta < 20°$ where this explanation is not available.

The reasons for this discrepancy are uncertain. Perhaps the most obvious explanation is that the data from Sweetser et al. are from regions of the earth other than the Basin and Range; and that in regions other than the Basin and Range the codas decay more slowly. This explanation would be consistent with the hypothesized low-Q nature of the Basin and Range suggested by, for example, Der, Massé and Gurski (1974), and with the higher complexity of codas in the Basin and Range that Blandford and Sweetser (1975) observed. Also, variations in crustal structure and amplitudes of P_g might be important. In sum, these results imply that for strict validity regional codas should be regionalized.

Still another possible explanation for the discrepancy is that earlier measurements of coda did not strictly adhere to the requirement that amplitude measurements be restricted to dominant periods of less than two seconds or that

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Der, Z.A., R.P. Massé and J.P. Gurski (1975), Regional attenuation of short-period P and S waves in the United States, Geophys. J.R. Astr. Soc., v. 40, p. 85-106.

noise contaminated the longer-time measurements. However, a review of the original data for the distance range 14-16° used by Sweetser et al. (1973) showed that this was not the case. Several errors were uncovered which lowered the estimated mean coda. However, it was reduced only to a level slightly above the 16-21° mean determined in that report.

Therefore, because Basin and Range codas appear to fall off rapidly, a real difference exists between Basin and Range codas and world-wide average codas. Thus, these codas, if used in future evasion scenarios, will lead to underestimations of evasion opportunities in most other regions of the world.

The distance range 14.3-21.0° presents a special difficulty in determining an asymptotic coda slope. Simple extrapolation like that used for the two previous coda ranges, yields an unreasonable zero slope. Therefore, we chose to use 0.06, which was the average three-to-five minute slope for the distance range 16-21° from Sweetser et al. (1973). This value seems reasonable because it is located about half way between the 10.7-14.3° slope of 0.15, and the 21-180° slope of 0.034.

Beginning at 42° large coda measurements, signified by the letter "L" next to the number of coda, are used to extend small coda measurements beyond the point where over half of the small coda measurements are not available. This extension is done by shifting the mean large coda to the left by two minutes (two minutes is conservative, minimizing the number of opportunities), an act consistent with the results of Sweetser and Cohen (1974b). Notably, these average large-event slopes are very close to 0.034 magnitude units per minute. The large-event codas are carried out to the point where just over half of the original large-event coda measurements can still be made; they are then extrapolated with the 0.034 slope.

The large coda means begin on page A-11. The distance range notations of all the large coda measurements out to 42° have the parenthetical notation (SA), standing for "small, adjusted." Since no measurements for large events were available in this distance range, large coda shapes for practical use were derived in the following way: Inspection of the large coda shapes at larger distances reveals that they typically start at about thirty-three per cent and grow in fifteen seconds to a maximum of about seventy per cent.

Therefore, the large codas start at thirty-three per cent, or, at the value of the small event coda mean for the same distance range. (if it starts at a smaller value.) The large-event coda grow to the maximum percent of the small event mean coda in fifteen seconds. This value is maintained as a constant until one minute after the occurrence of the small event maximum. From this point the small event coda are displaced one minute (one minute is conservative, thus minimizing the number of opportunities) to the right and used as the large event coda.

In the ranges 42.6-53.0°, 63-67°, 72-79°, and 79-84°, the 1964 Alaskan earthquake codas are plotted along with the mean large-event codas. Sweetser and Cohen (1974) also plotted and discussed the Alaskan earthquake codas. Codas show that this exceptionally large earthquake did not rise to the maximum amplitude until one or two minutes passed. Furthermore, note that if the maximum amplitude were used instead of the amplitude in the first five seconds to determine m_b, then for these stations the average magnitude would change from 6.7 to 7.7. If the typical high-amplitude duration for this event was taken to be two minutes, as compared to five seconds for the typical small event, then the Alaskan earthquake had $10^2 x(120/5)=2400$ times as much 1 Hz energy as a typical m_b 6.7 earthquake. Blandford and Clark (1975) have already discussed that a new definition of m_b which more accurately reflects the 1 Hz energy in the P wave, should significantly tighten the $M_s:m_b$ diagram. Also, assuming that the conventional m_b has any simple relationship to total 1 Hz energy can lead to incorrect conclusions about corner frequency.

These coda shapes provoke a problem that is beyond the scope of the study, but still requires discussion: that is, whether these coda shapes may serve as a discriminant between earthquakes and explosions. Many authors have found that at regional distances ratios between the compressional phases, e.g. P_n, P_g; and the later shear-dominated phases, S_n, L_g, etc. can serve as a discriminant even though the shear phases are measured on the vertical component. Brune, Espinosa, and Oliver (1963) assert that the amplitudes for the later

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Brune, J., A. Espinosa, and J. Oliver, (1963) Relative excitation of surface waves by earthquakes and underground explosions in the California-Nevada region, J. Geophys. Res., 68, p. 3501-3513.

arriving phases are about the same on all three components. See, also for example, Willis (1963), Willis, DeNoyer, and Wilson (1963), Booker and Mitronovas (1964), Pasechnik (1970), and Lambert and Becker (1975).

For purposes of discrimination included in Figure 2 are the earthquake and explosion coda for the close-in distances. A procedure for analyzing these graphs for their discrimination potential is as follows: First, align the average coda on the amplitude at "0" (the maximum in the time interval 0-5 seconds). Then scan the two mean amplitude curves to determine if the mean earthquake coda fell outside the one standard deviation (0.3 $\log_{10}$) of an individual observation error limits for the explosion coda. No stable difference between the coda shapes useful for discrimination was noted.

A second analysis procedure was similar because the maximum amplitude before the arrival of S_n were aligned. In Figure 2, where this alignment was chosen, is found a possibility of discrimination that agrees with earlier studies. In the late time intervals appropriate for shear arrivals, the earthquakes have larger amplitudes.

The differences noted are probably big enough to serve as discriminants if network averaged. At single stations a standard deviation of one observation of 0.3 would lead to many incorrect classifications. In Appendix I the earthquake and explosion codas have been averaged together. A more careful analysis would use the coda in Figure 2 as appropriate.

Willis, D. E., (1963) Comparison of seismic waves generated by different types of source, BSSA, 53, p. 965-986.

Willis, D. E., J. DeNoyer, J. T. Wilson, (1963) Differentiation of earthquakes and underground nuclear explosions on the basis of amplitude characteristics, BSSA, 53, p. 979-987.

Booker, A., and W. Mitronovas, (1964) An application of statistical discrimination to classify seismic events, Bull. Seism. Soc. Am., 54, p. 961-971.

Pasechnik, I. P., (1970) Characteristics of seismic waves from nuclear explosions and earthquakes, Nauka, Moscow. Translated by C. Shishkevish, Geosciences Bulletin, Series A, Volume 1, Rand Corporation, Washington, D.C.

Lambert, D. G. and E. S. Becker, (1975) Basic seismic analysis of regional events observed at NORSAR, Technical Report Number 4, Texas Instruments, Alexandria, Virginia.

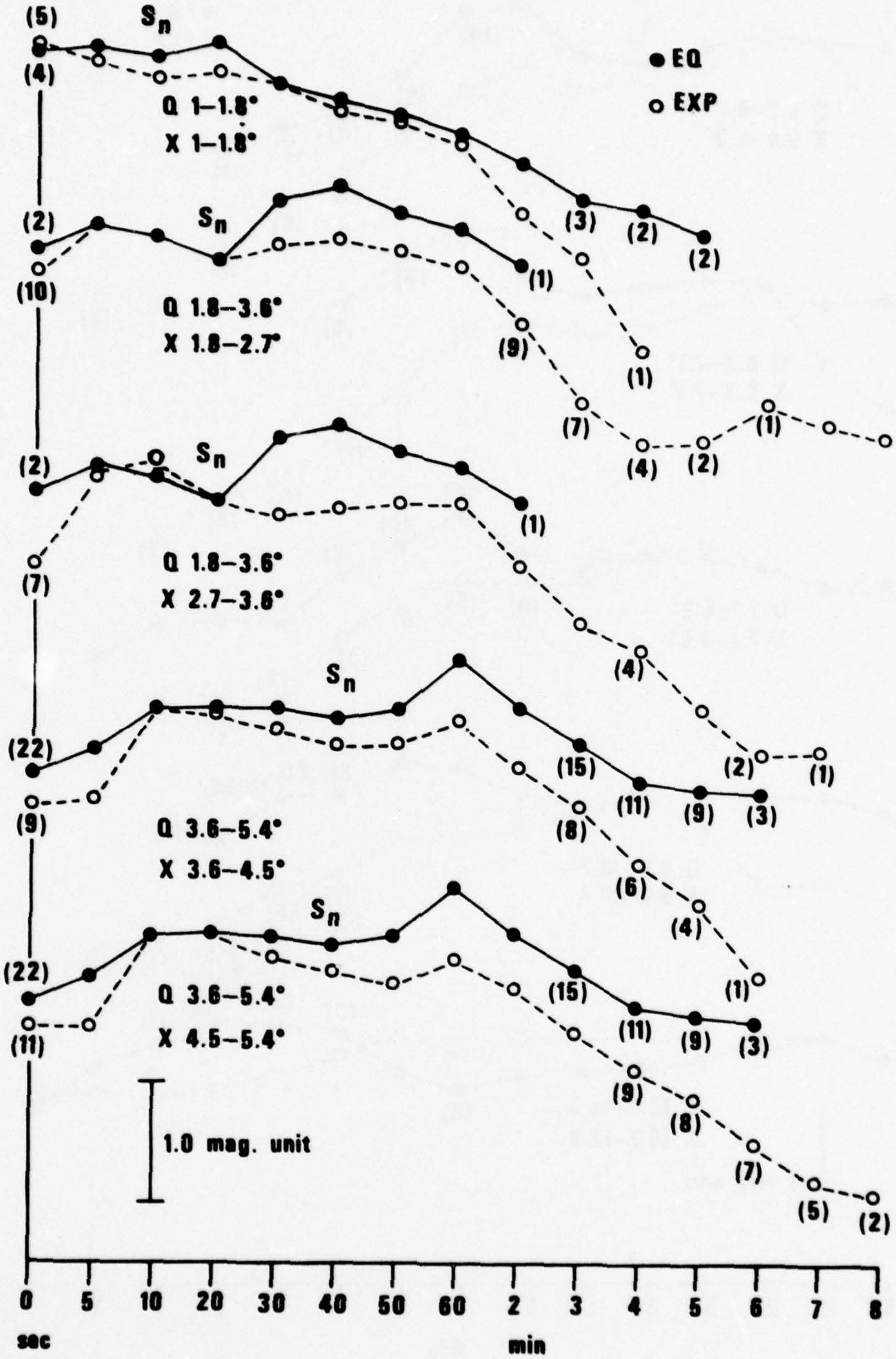


Figure 2. Earthquake coda amplitudes relative to explosion coda amplitudes. Plotted points at time t_n represent average $\log_{10}$ relative amplitude in the time interval t_n to t_{n+1}. Maximum coda aligned for time interval before earliest arrival of S_n for coda in the distance interval so long as S_n - P_n time is less than one minute. If S_n - P_n time is greater than one minute, the coda are aligned on the maximum in the first minute.

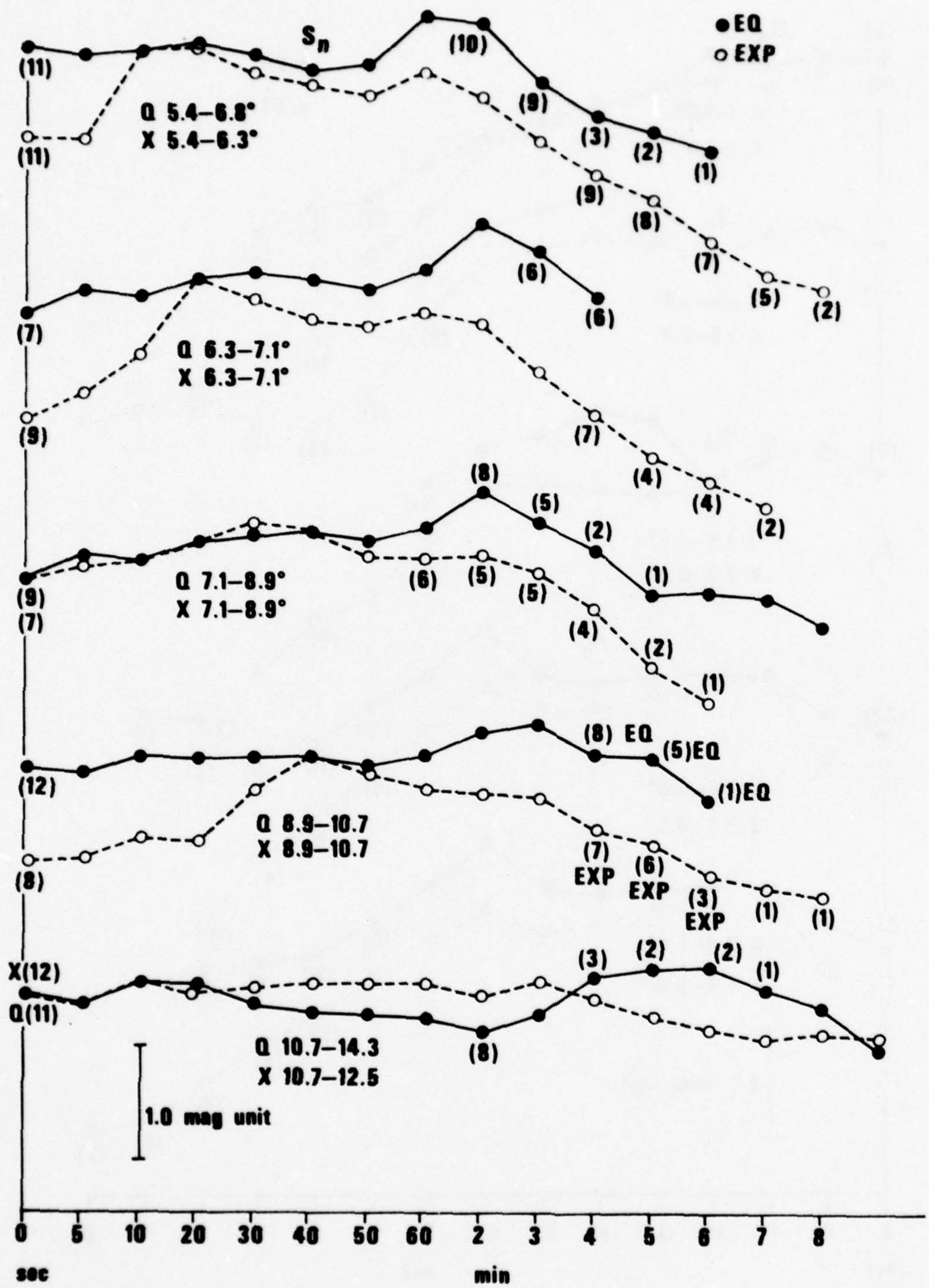
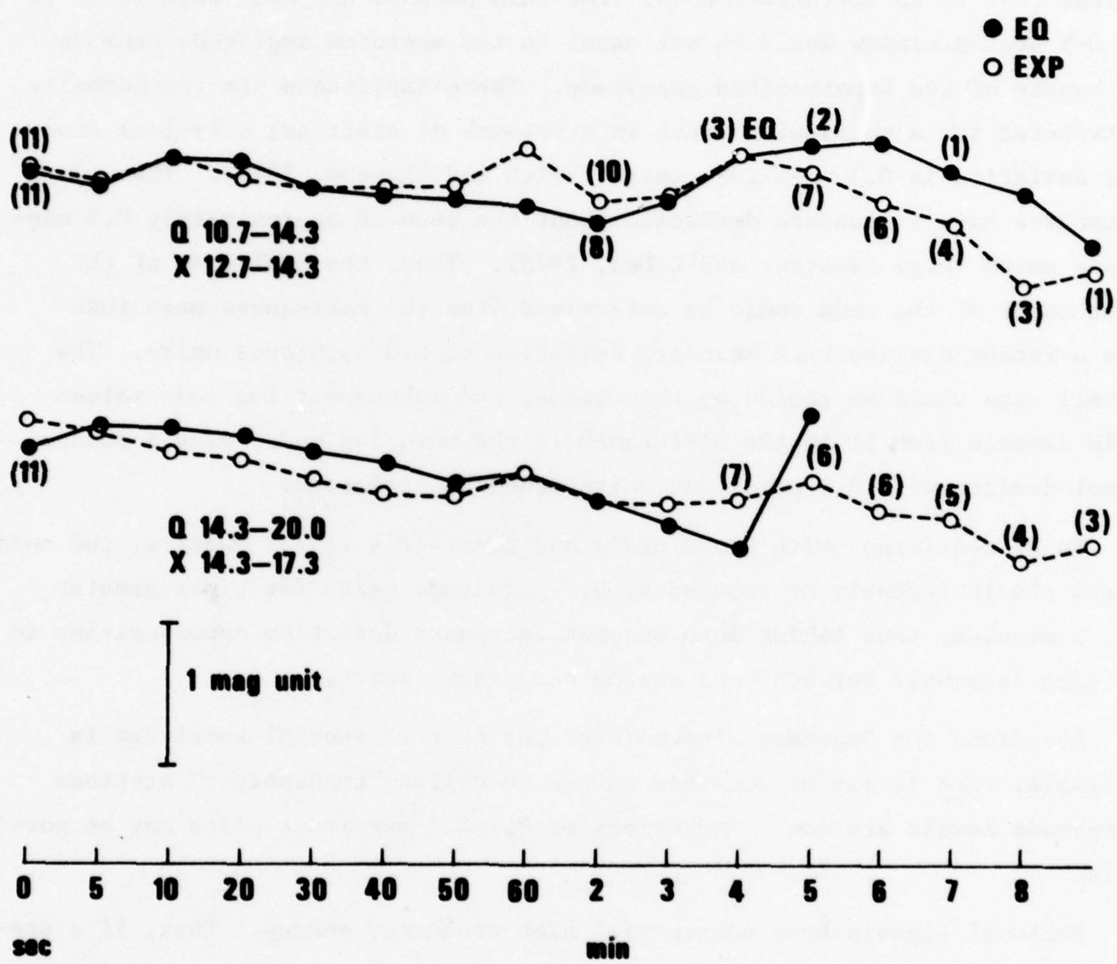


Figure 2 (cont.) Earthquake coda amplitudes relative to explosion coda amplitudes. Plotted points at time t_n represent average $\log_{10}$ relative amplitude in the time interval t_n to t_{n+1}. Maximum coda aligned for time interval before earliest arrival of S_n for coda in the distance interval so long as $S_n - P_n$ time is less than one minute. If $S_n - P_n$ time is greater than one minute, the coda are aligned on the maximum in the first minute.



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REMARKS ON USAGE

These mean coda should be used in attempts to predict the number of opportunities that an evader might have each year to hide the signal from a nuclear test in an earthquake coda. For this purpose the mean coda level in the 0-5 second window would be set equal to the expected amplitude from an earthquake of the hypothesized magnitude. These amplitudes are log-normally distributed for a particular event at a network of stations; a typical standard deviation is 0.3 magnitude units (Veith and Clawson, 1972). The coda themselves have a standard deviation about the mean of approximately 0.2 magnitude units (e.g. Sweetser and Cohen, 1973). Thus, the amplitude of the first point of the coda would be determined from the earthquake magnitude plus a random deviate with standard deviation of 0.3 magnitude units. The overall coda would be scaled by this value, and subsequent log coda values would deviate from it by the difference in the mean log coda, plus a random normal deviate with 0.2 magnitude units standard deviation.

To be consistent with Blandford's and Sweetser's (1975) results, the coda levels should probably be reduced by 0.2 magnitude units for times greater than 2 minutes, thus taking into account increased detection opportunities in the time intervals between coda maxima one minute apart.

Blandford and Sweetser also pointed out that if special knowledge is available, then it may be possible to use so-called "transparent" stations where coda levels are low. Reductions of 0.1-0.2 magnitude units may be possible.

Regional signals have substantial high frequency energy. Thus, if a station is at regional distance from an explosion, then the coda shapes given in this report will be unsuitable for teleseismic earthquakes where the low frequency signal will not hide the high frequency signal from the explosion. A "frequency gain" factor needs to be estimated and used.

Blandford and Clark (1975) have shown that LASA coda from some small regions of Kamchatka are very simple. Special knowledge of this kind could greatly

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Veith, K. F. and G. E. Clawson (1972), Magnitude for short-period P-wave data, Bull, Seism. Soc. Am., v. 62, p. 435-452.

reduce the number of estimated evasion opportunities in selected small regions and enable careful scrutiny of the coda of events from more "complex" regions.

With the advent of the world-wide Seismic Research Observatory (SRO) systems opportunities exist to estimate the ease with which an explosion may be hidden in an earthquake by direct superposition of the digital data, short-period and long-period, from two events. Simple time-domain filtering may be easily applied to see if it improves detectability. These results may be compared to the predictions of earlier workers, and their predictive programs "calibrated" by comparison. These programs will continue to serve a useful purpose because they enable researchers to estimate the advantage gained from the addition of new stations to an existing network.

ACKNOWLEDGEMENTS

H. Husted wrote the programs to plot the coda in a convenient form, and E. Sweetser checked several of the coda from his earlier studies.

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APPENDIX

A1-A10	Small earthquake mean coda shapes	$m_b \leq 5.8$
A11-A20	Large earthquake mean coda shapes	$M_s \geq 7.0$

Notation

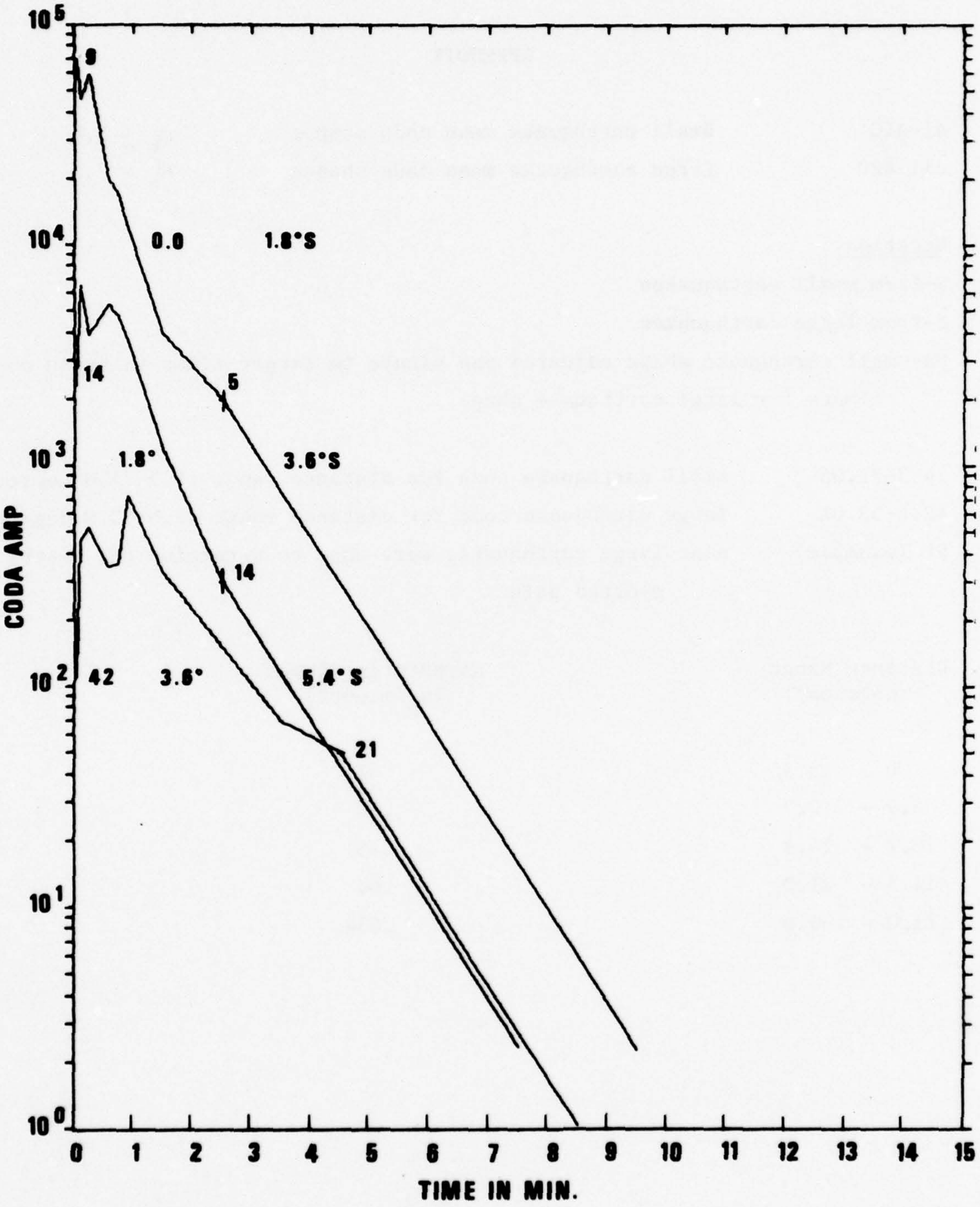
S-from small earthquakes

L-from large earthquakes

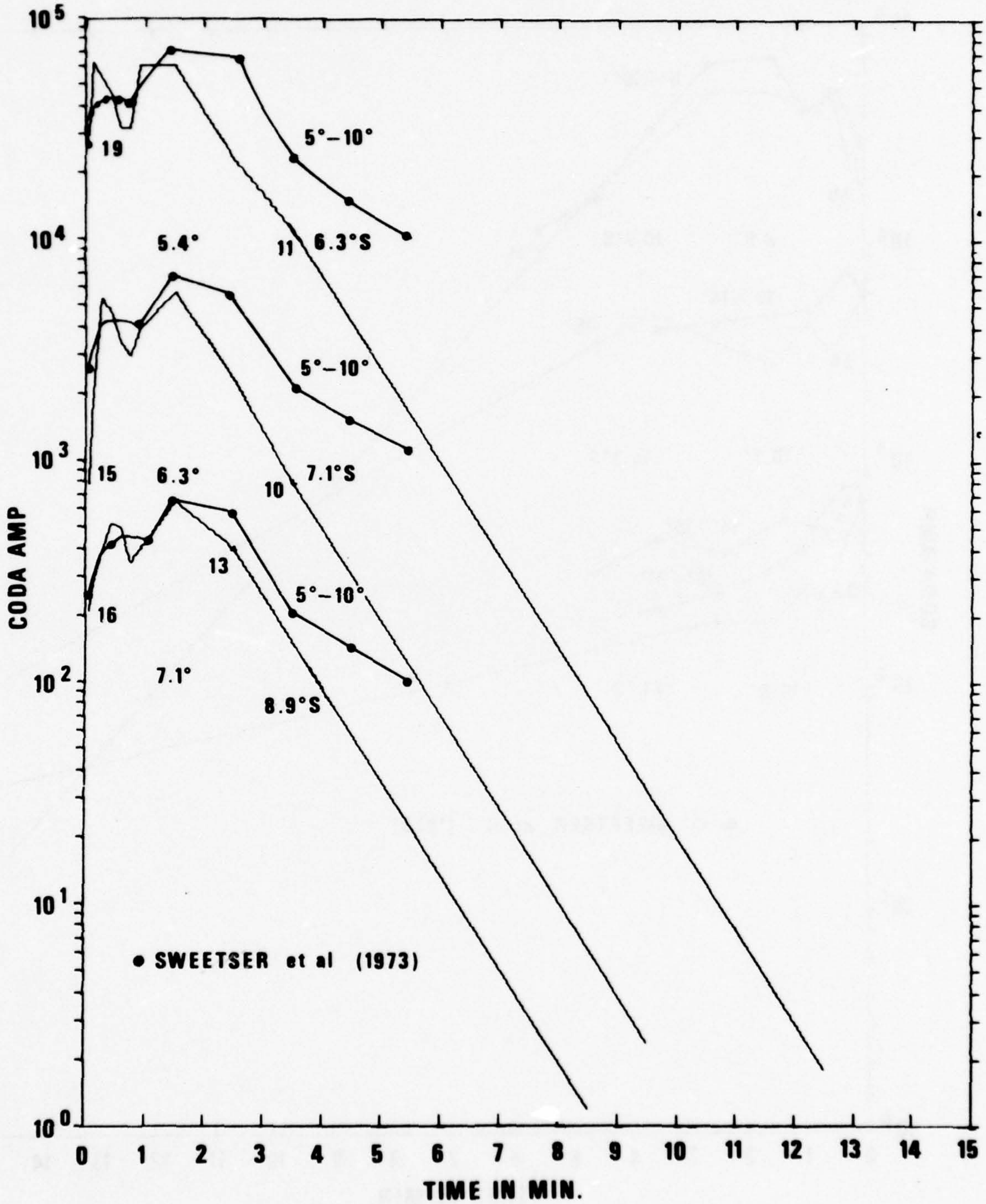
SA-small earthquake shape adjusted one minute to larger times to be an estimate for large earthquake shape

14.3-21.0S	small earthquake coda for distance range 14.3-21.0 degrees
42.6-53.0L	large earthquake coda for distance range 42.6-53.0 degrees
9L (example)	nine large earthquakes were used to determine the nearby plotted point

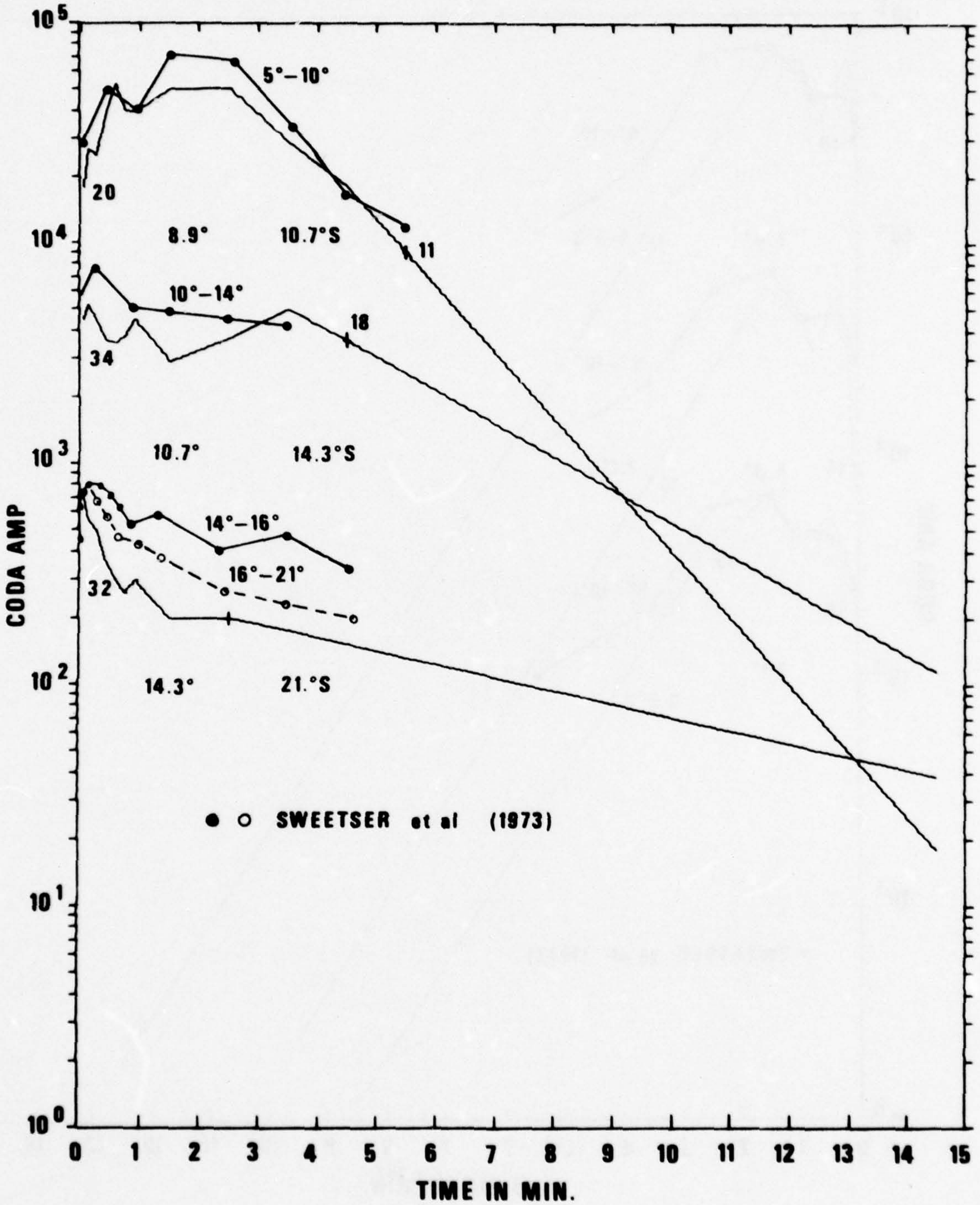
Distance Range (degrees)	Asymptotic Slopes (m_b/minute)
0 - 8.9	.42
8.9 - 10.7	.30
10.7 - 14.3	.15
14.3 - 21.0	.06
21.0 - 180.0	.034



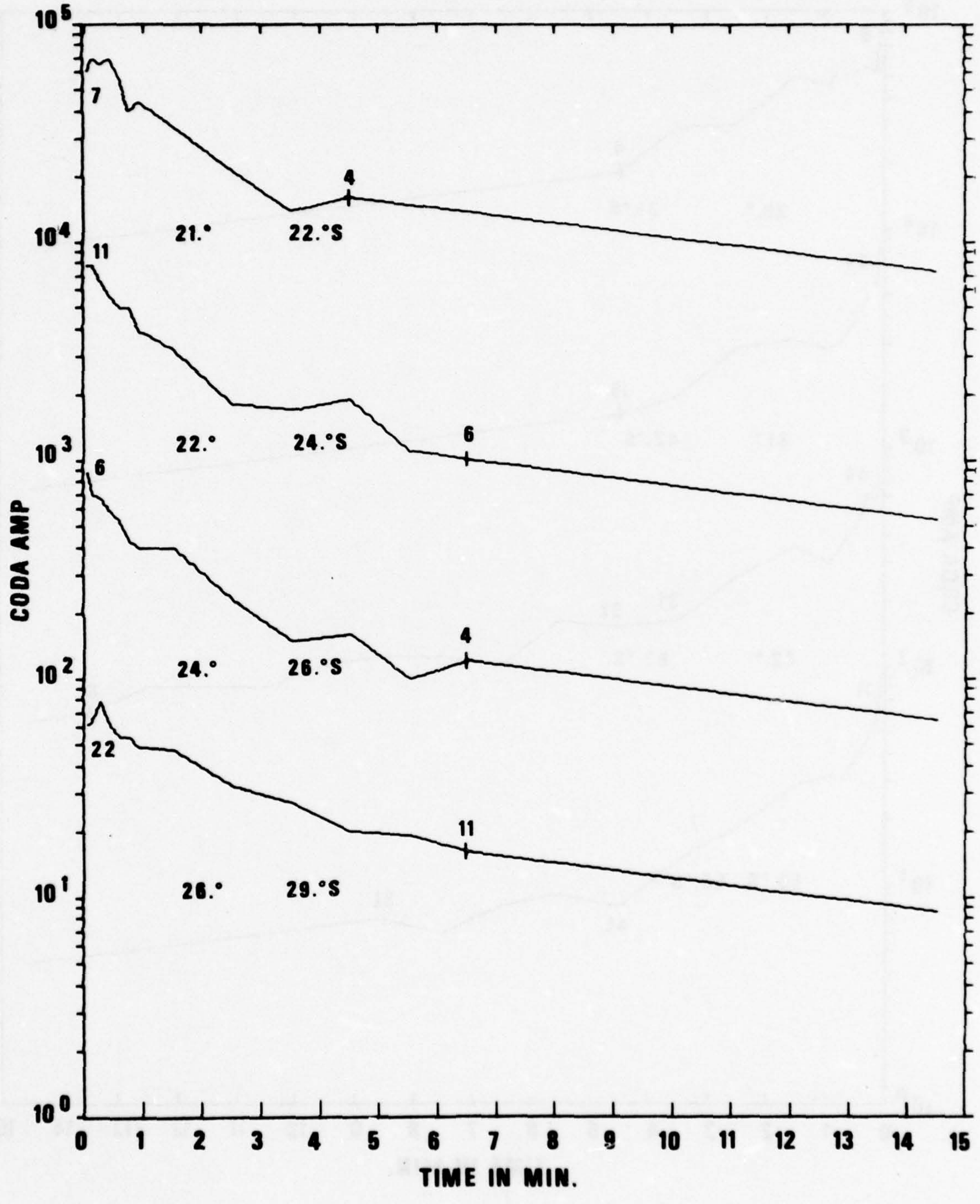
CODA AMP
TIME IN MIN.
10^5
10^4
10^3
10^2
10^1
10^0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
9
0.0
1.8°S
14
5
1.8°
3.6°S
14
42
3.6°
5.4°S
21



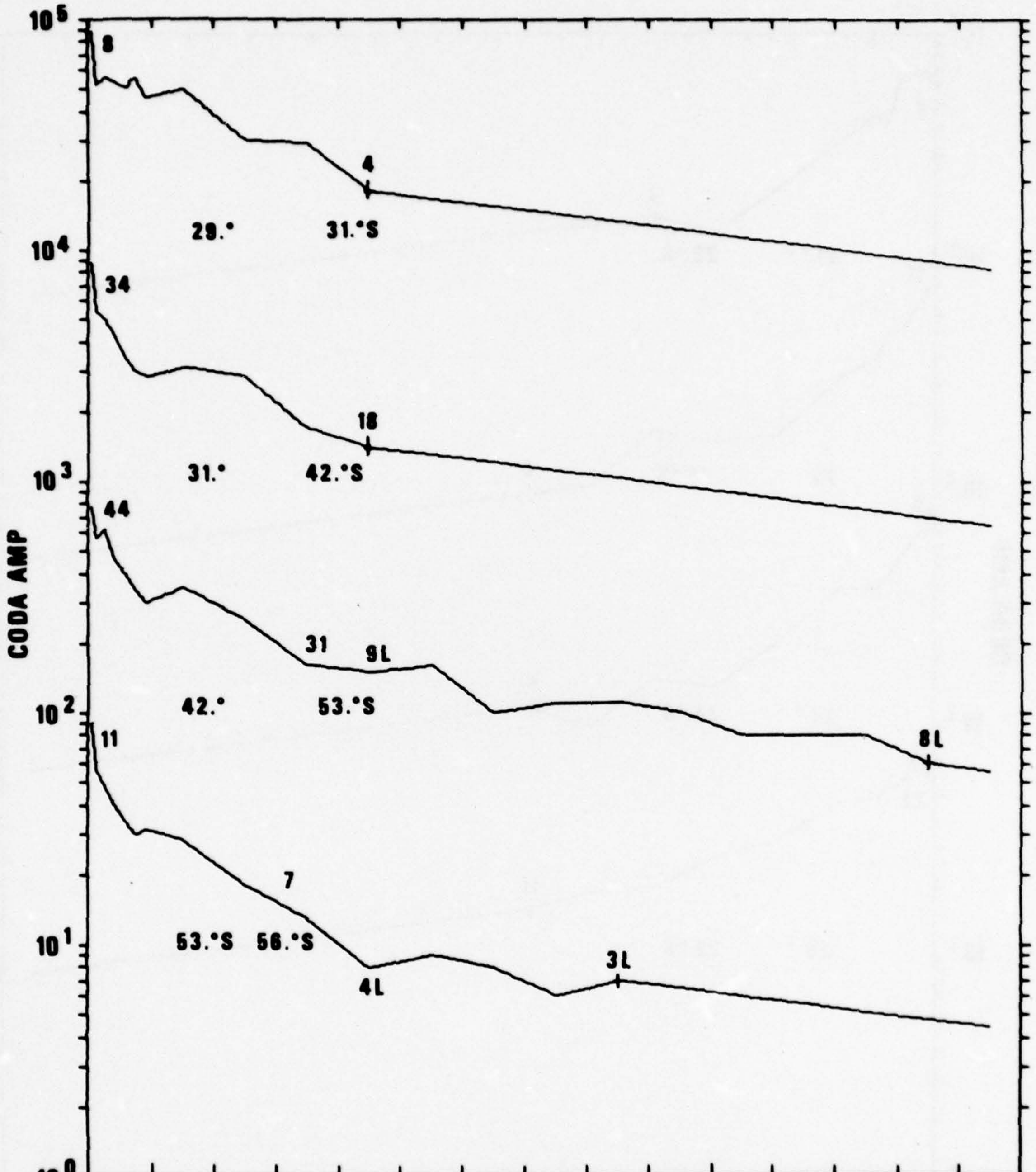
10 5
10 4
10 3
10 2
10 1
10 0
CODA AMP
TIME IN MIN.
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
19
5.4°
5°–10°
11
6.3°S
15
6.3°
5°–10°
10
7.1°S
16
7.1°
13
5°–10°
8.9°S
● SWEETSER et al (1973)

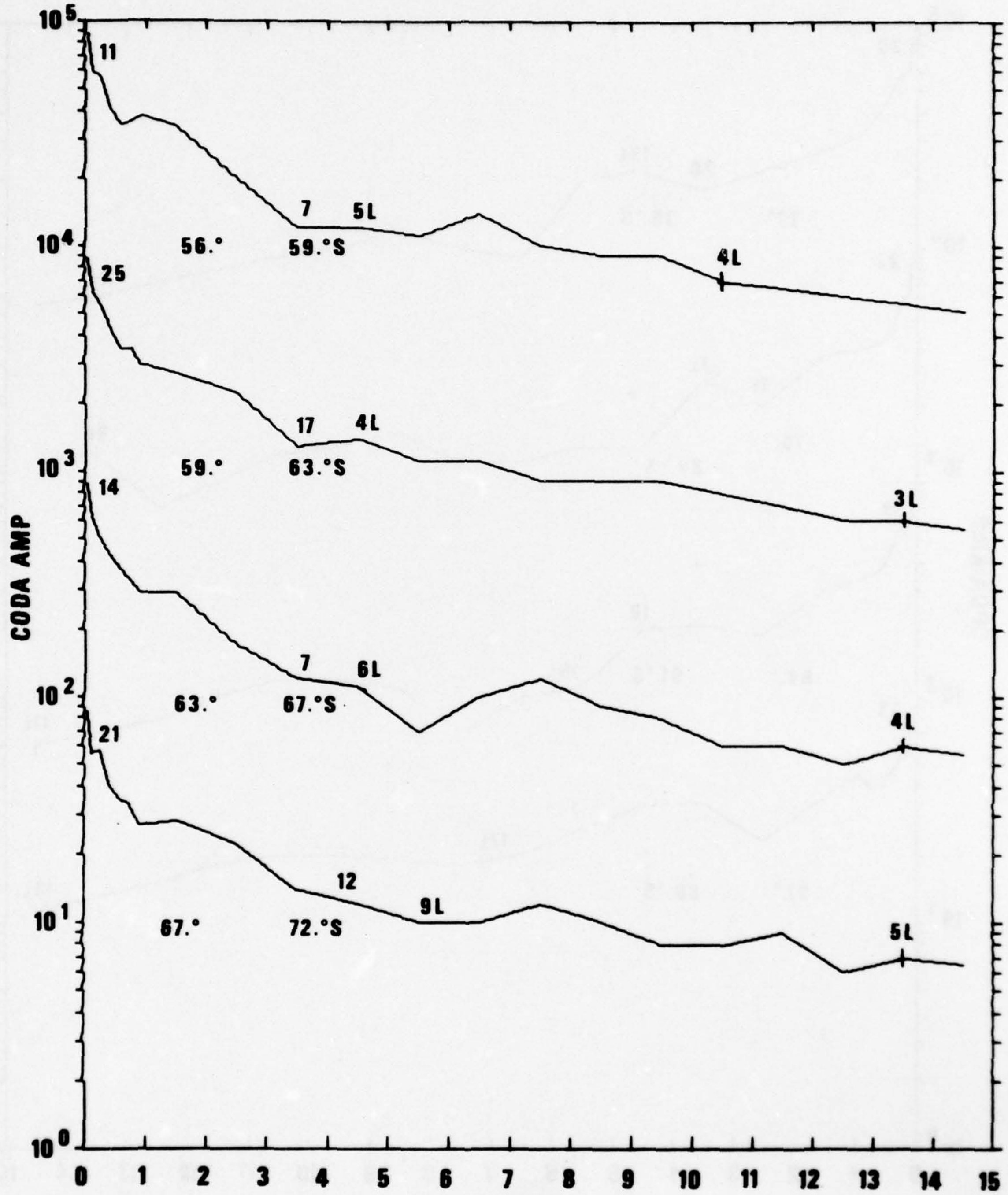


CODA AMP
TIME IN MIN.
5°–10°
20
8.9°
10.7°S
11
10°–14°
18
34
10.7°
14.3°S
14°–16°
16°–21°
32
14.3°
21.°S
SWEETSER et al (1973)

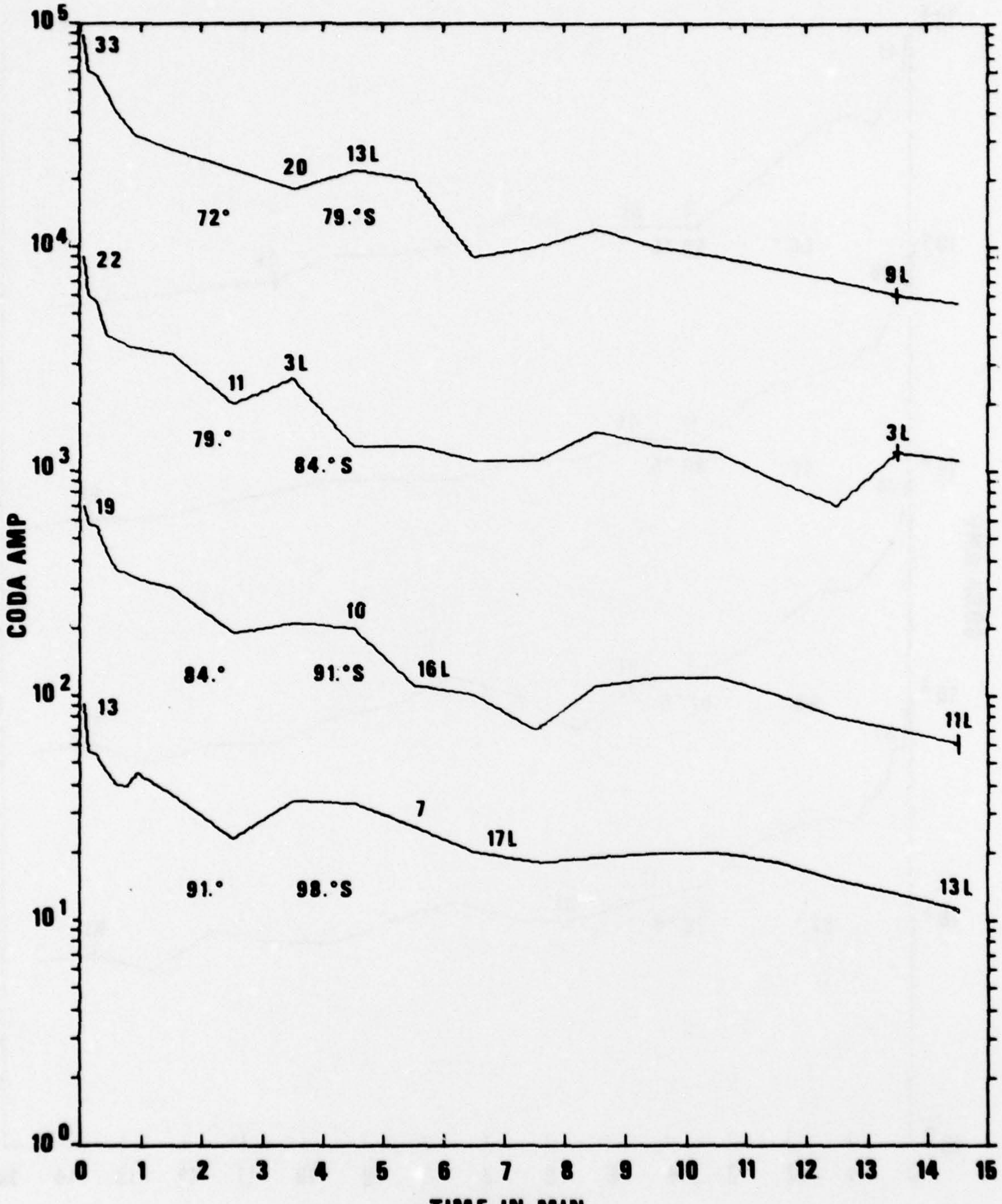


CODA AMP
TIME IN MIN.
21.°
22.°S
22.°
24.°S
24.°
26.°S
26.°
29.°S

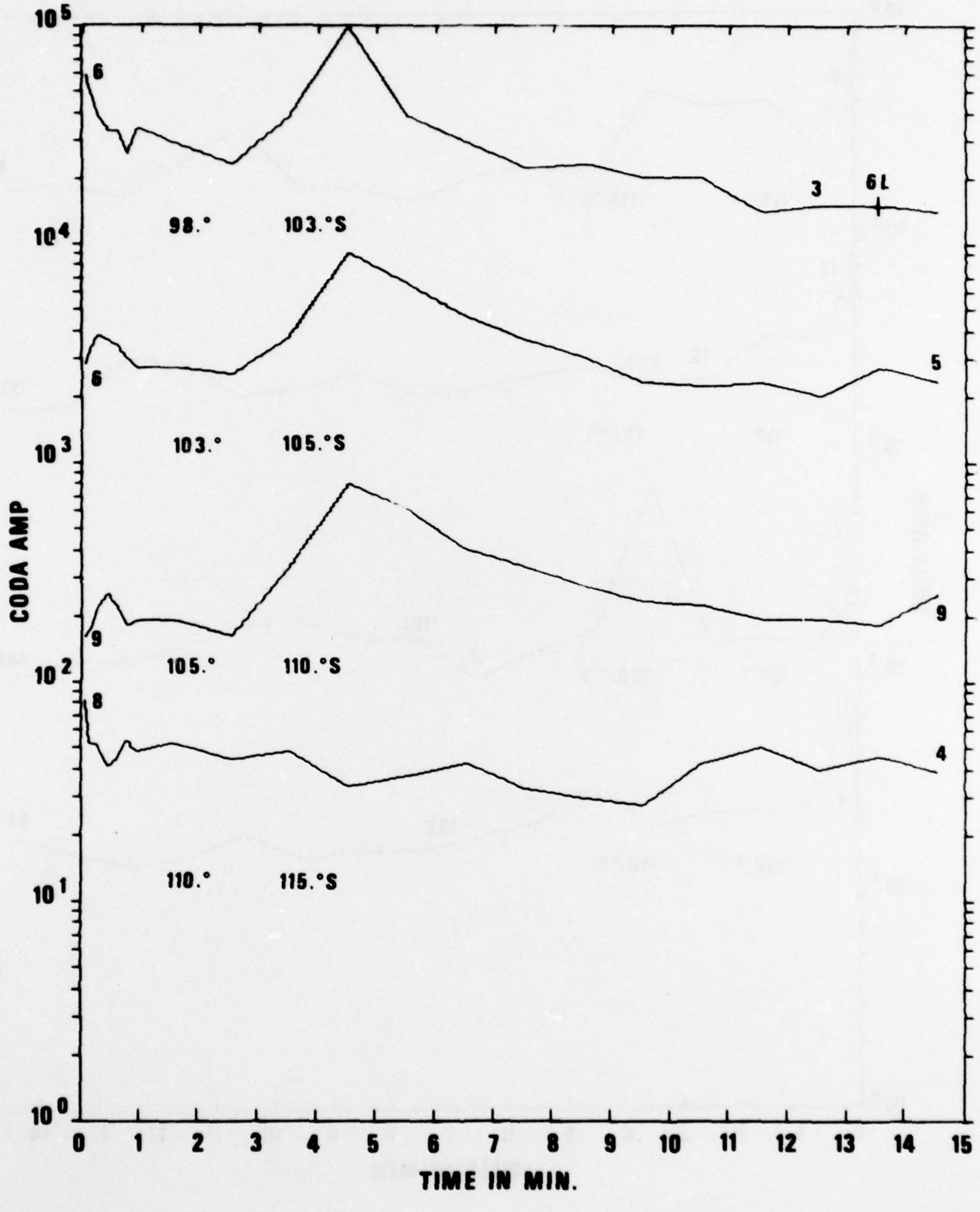

CODA AMP
TIME IN MIN.
8
4
29.°
31.°S
34
18
31.°
42.°S
44
31
9L
42.°
53.°S
8L
11
7
53.°S
56.°S
4L
3L



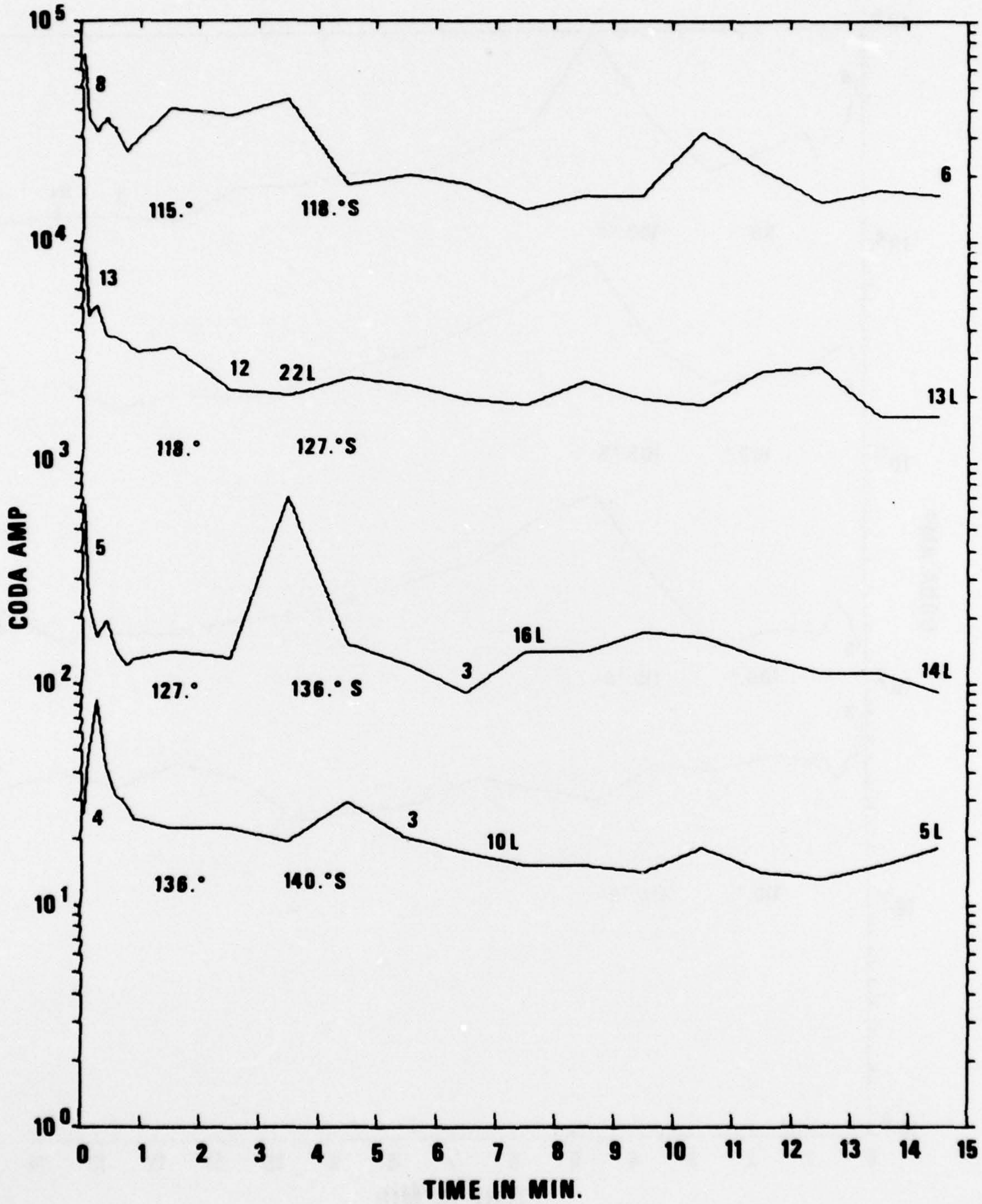
CODA AMP
TIME IN MIN.
10^5
10^4
10^3
10^2
10^1
10^0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
11
7
5L
56.°
59.°S
4L
25
17
4L
59.°
63.°S
3L
14
7
6L
63.°
67.°S
4L
21
12
9L
67.°
72.°S
5L



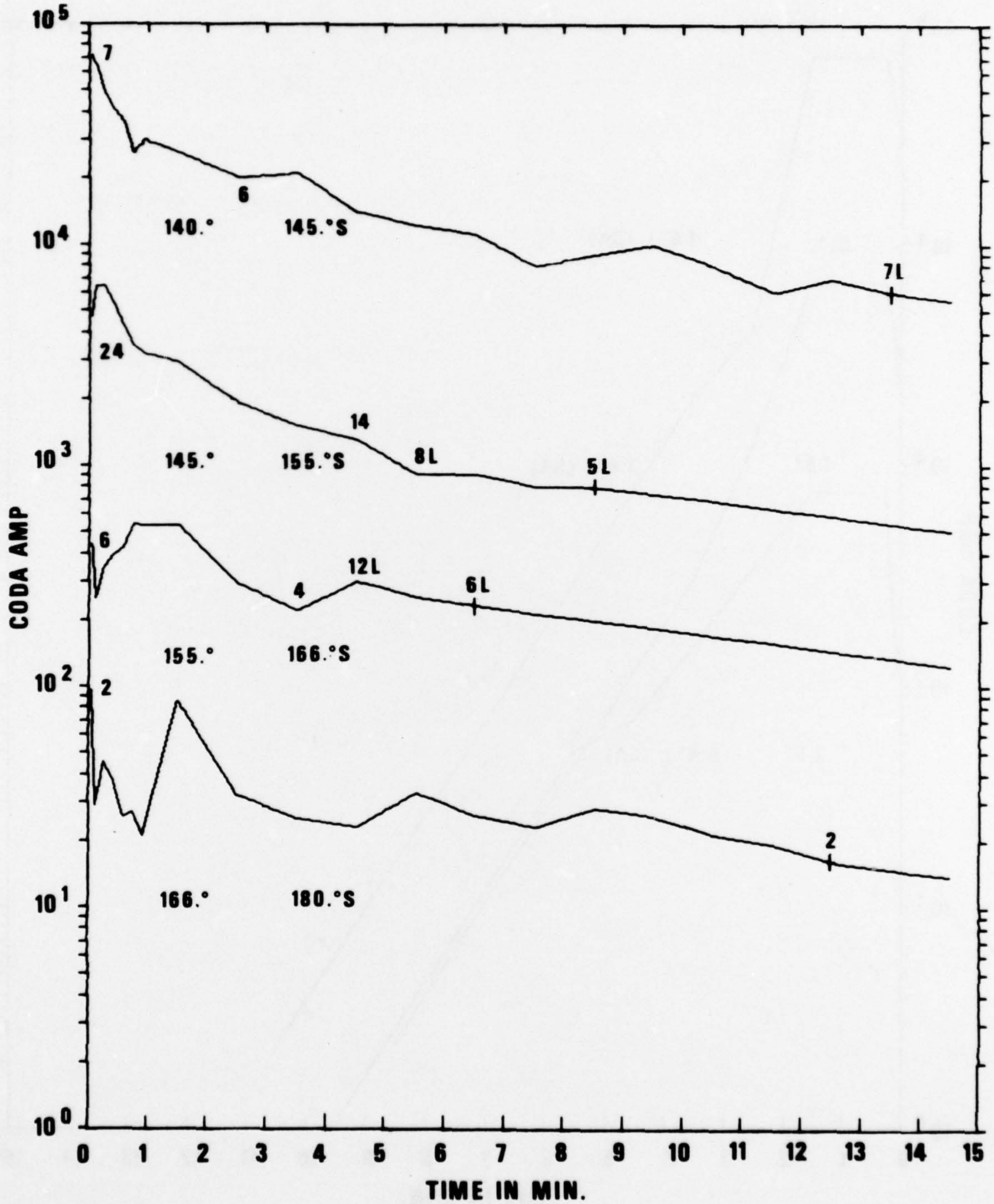
10^5
10^4
10^3
10^2
10^1
10^0
CODA AMP
33
20
13L
72°
79.°S
9L
22
11
3L
79.°
84.°S
3L
19
10
84.°
91.°S
16L
11L
13
7
17L
91.°
98.°S
13L
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
TIME IN MIN.



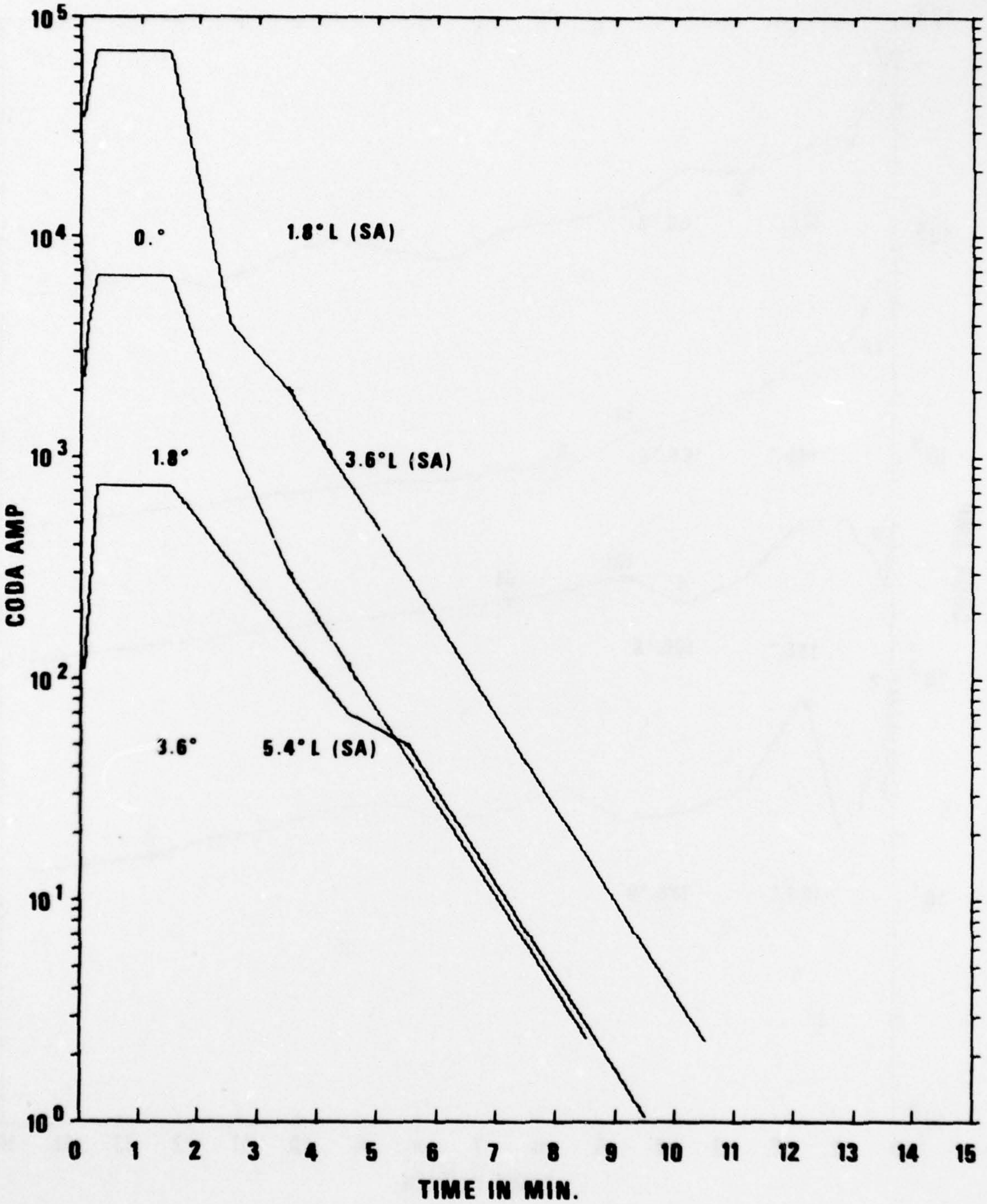
CODA AMP
TIME IN MIN.
98.°
103.°S
103.°
105.°S
105.°
110.°S
110.°
115.°S
3
6L



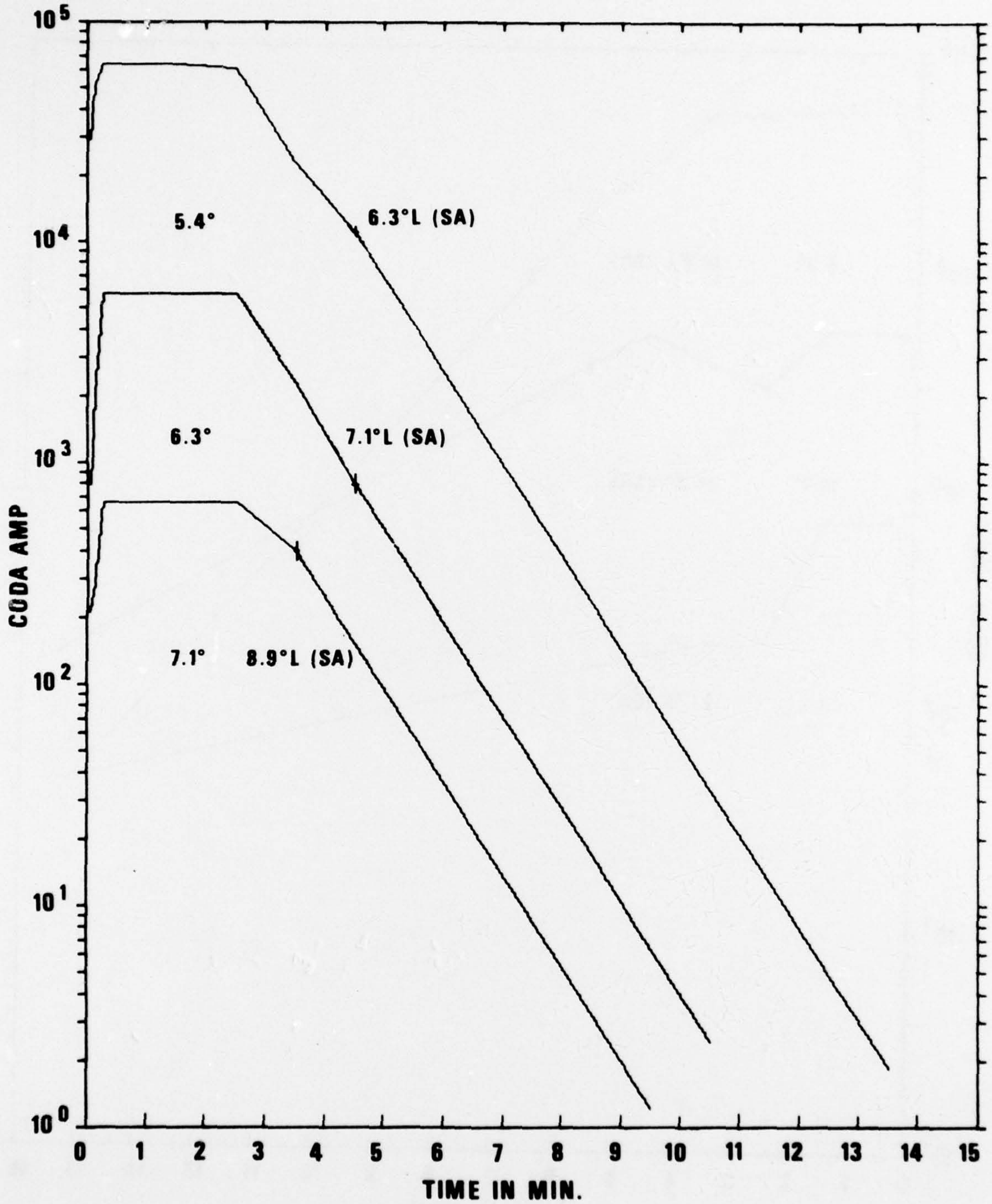
10^5
10^4
10^3
10^2
10^1
10^0
CODA AMP
8
115.°
118.°S
6
13
12
22L
13L
118.°
127.°S
5
16L
3
14L
127.°
136.° S
4
3
10L
5L
136.°
140.°S
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
TIME IN MIN.



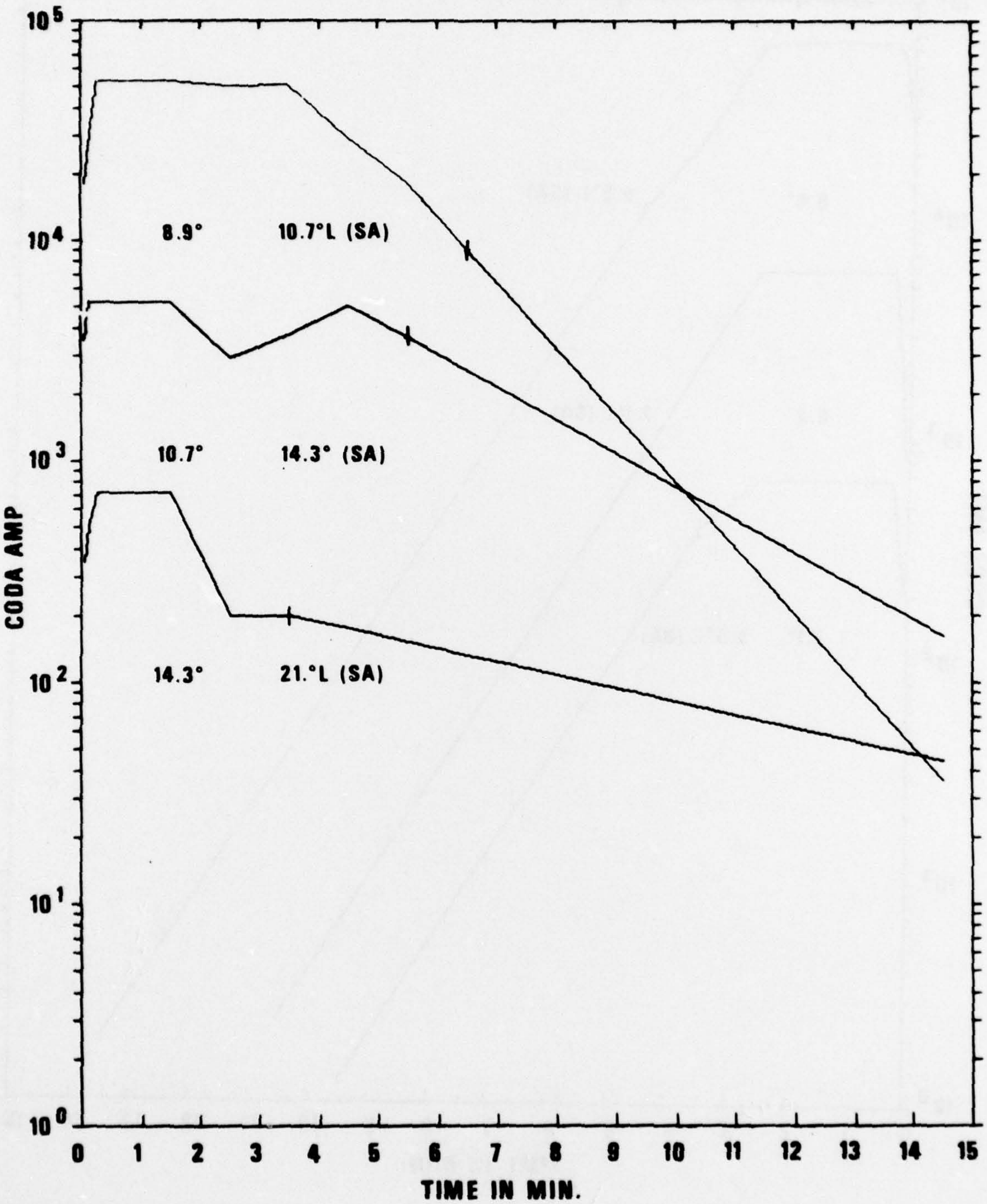
CODA AMP
TIME IN MIN.
7
6
140.°
145.°S
7L
24
14
145.°
155.°S
8L
5L
6
4
12L
6L
155.°
166.°S
2
2
166.°
180.°S



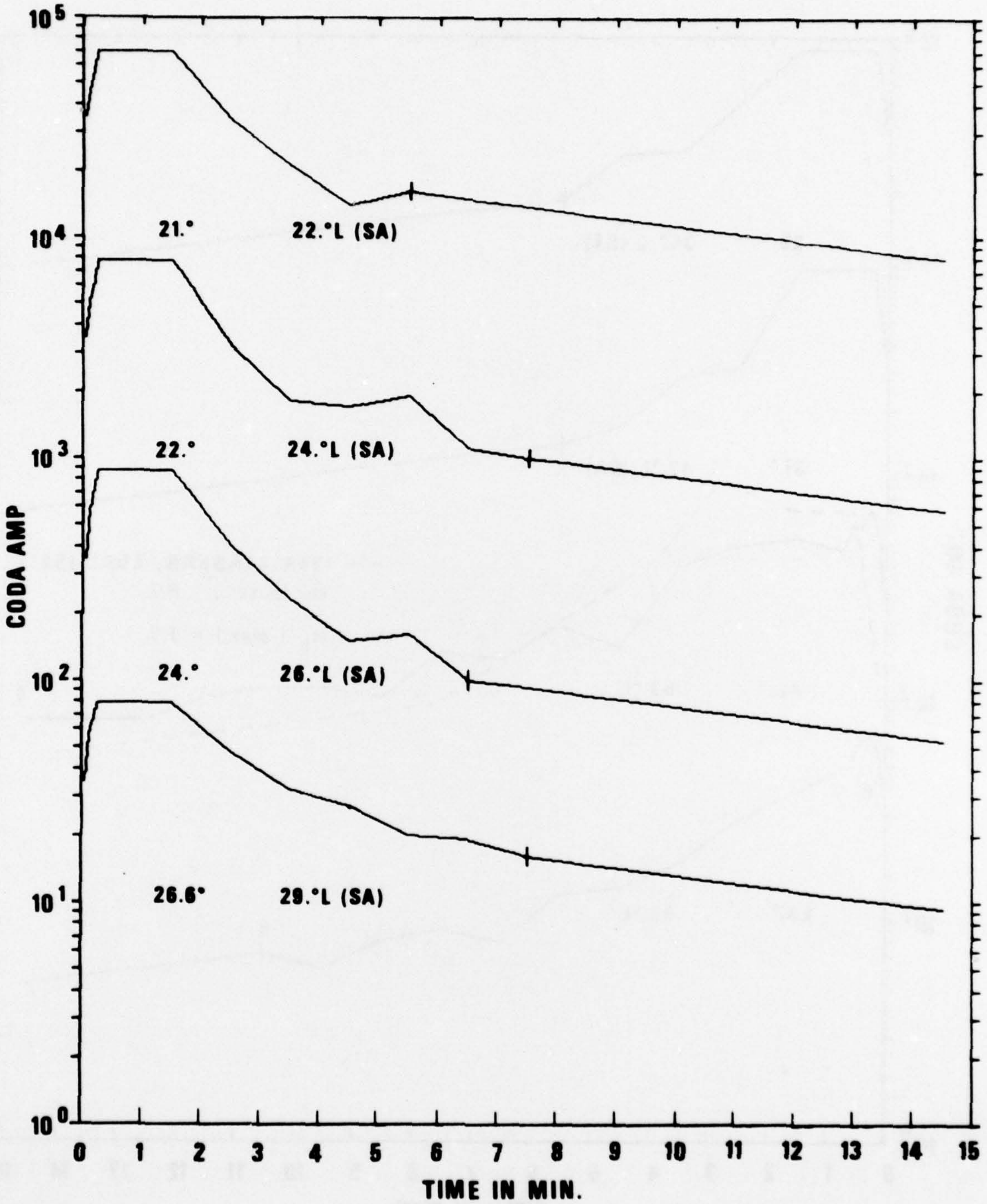
10^5
10^4
10^3
10^2
10^1
10^0
CODA AMP
0.°
1.8°L (SA)
1.8°
3.6°L (SA)
3.6°
5.4°L (SA)
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
TIME IN MIN.

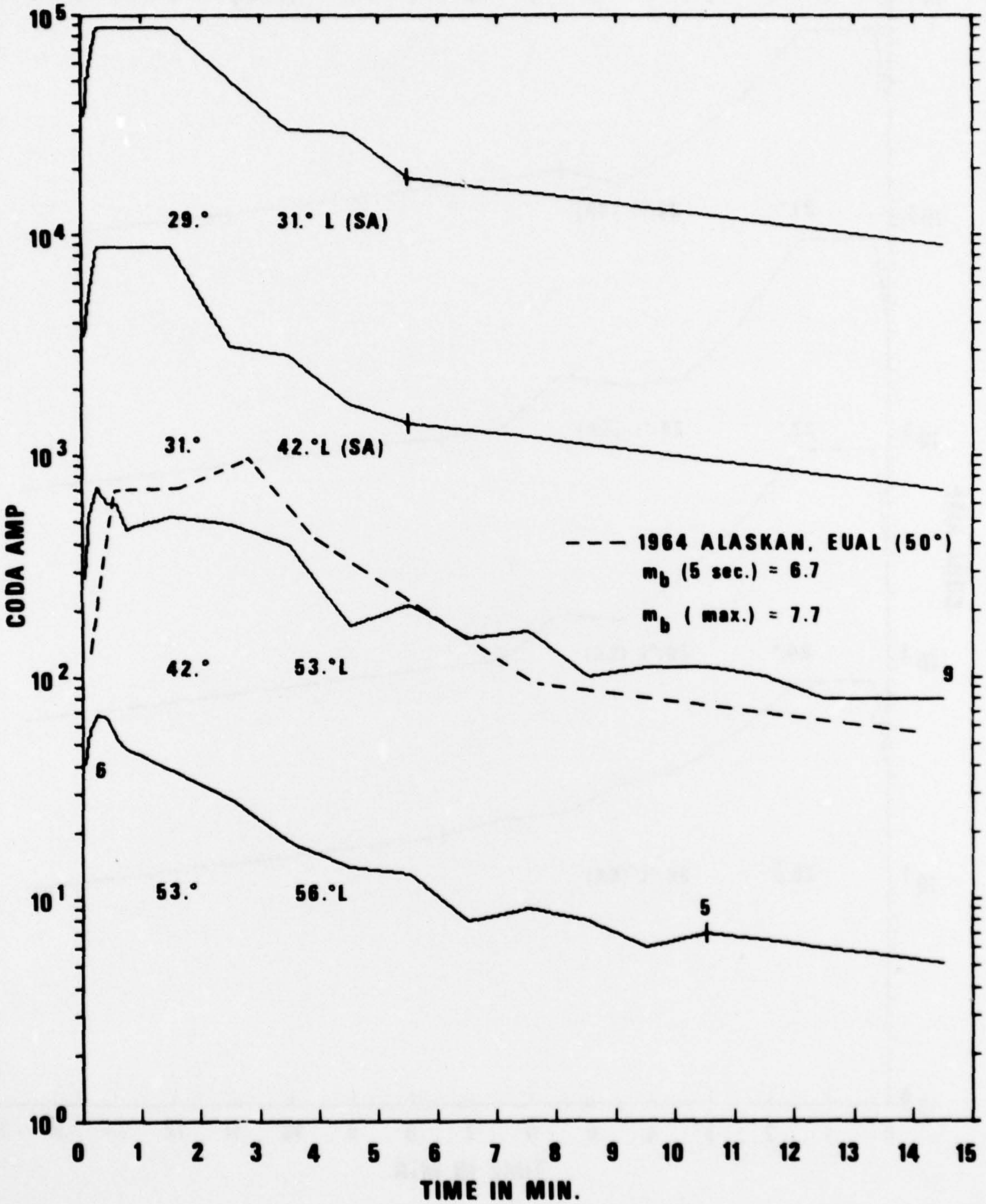


CODA AMP
10^5
10^4
10^3
10^2
10^1
10^0
5.4°
6.3°L (SA)
6.3°
7.1°L (SA)
7.1°
8.9°L (SA)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
TIME IN MIN.

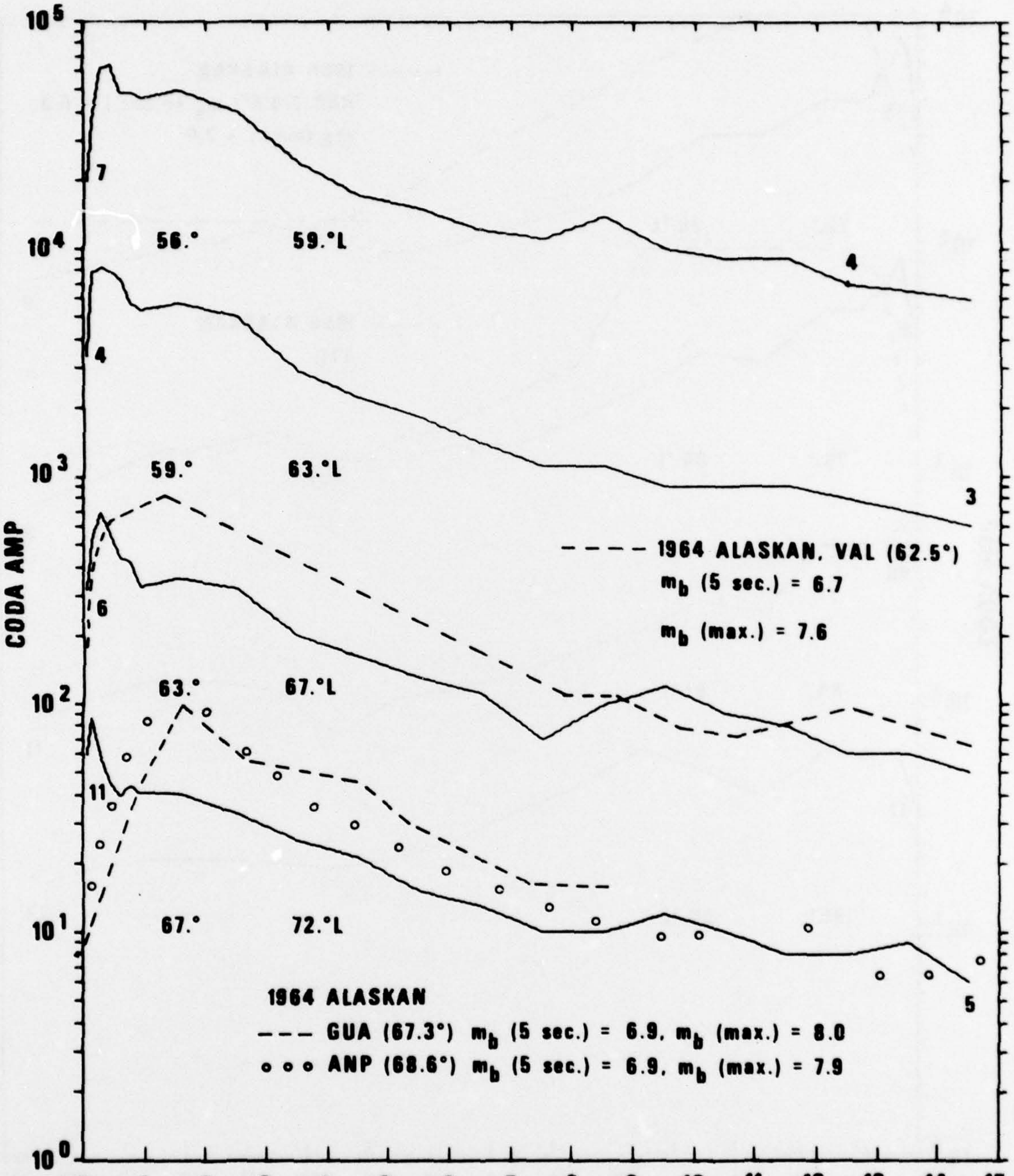


8.9°
10.7°L (SA)
10.7°
14.3° (SA)
14.3°
21.°L (SA)
CODA AMP
TIME IN MIN.

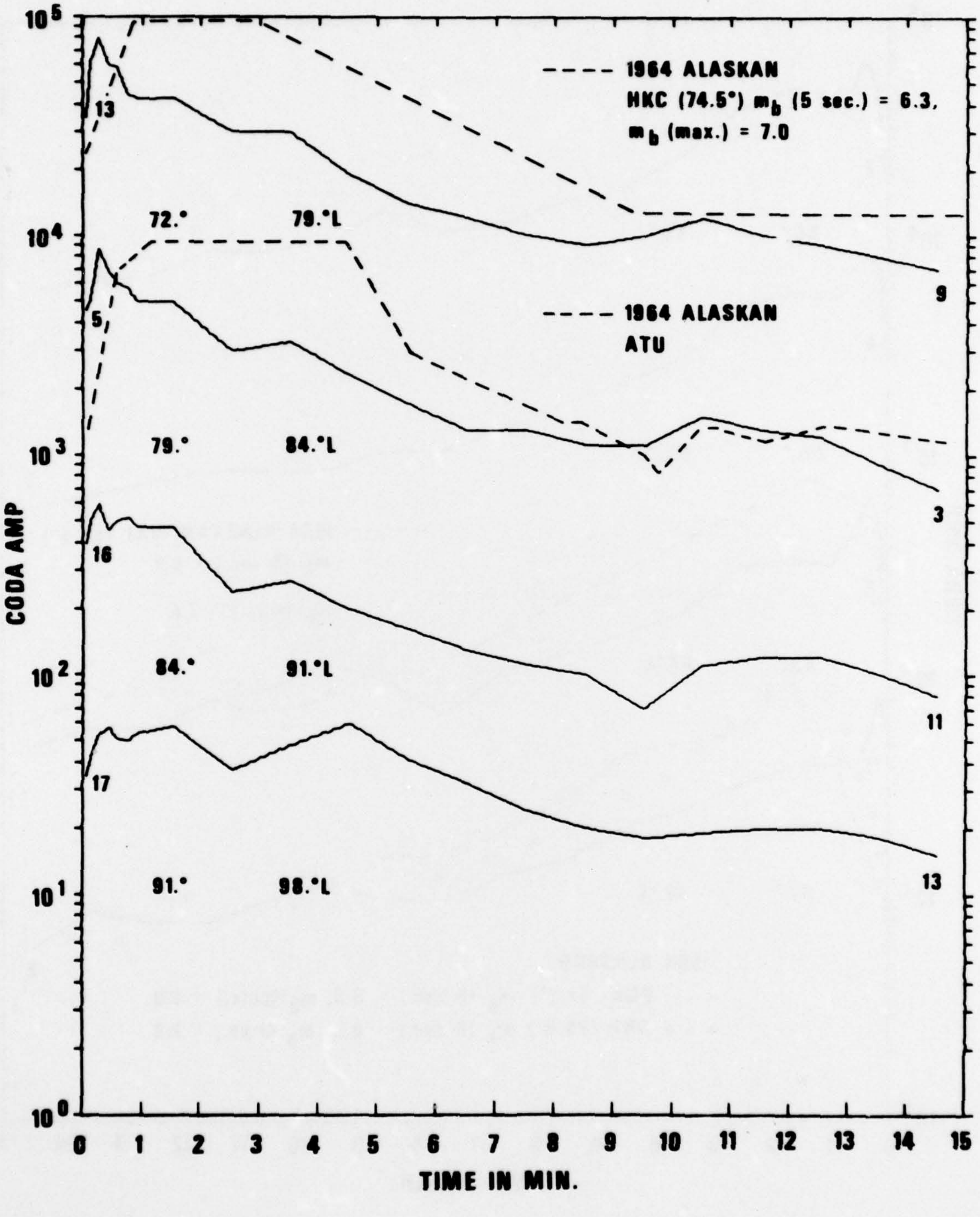

CODA AMP
21.°
22.°L (SA)
22.°
24.°L (SA)
24.°
26.°L (SA)
26.6°
29.°L (SA)
10^5
10^4
10^3
10^2
10^1
10^0
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
TIME IN MIN.



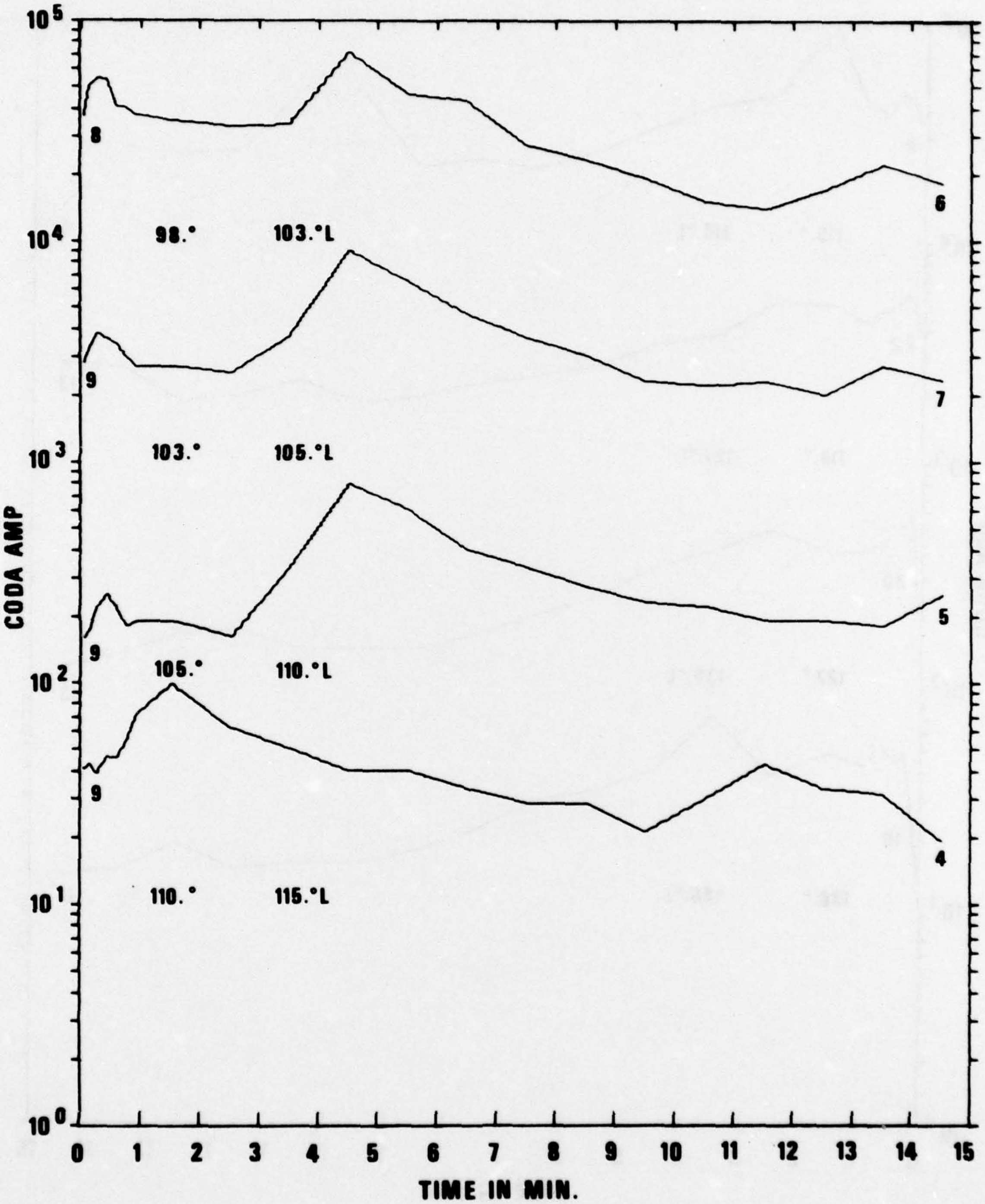
CODA AMP
TIME IN MIN.
29.°
31.° L (SA)
31.°
42.°L (SA)
42.°
53.°L
53.°
56.°L
1964 ALASKAN, EUAL (50°)
m_b (5 sec.) = 6.7
m_b (max.) = 7.7
9
6
5



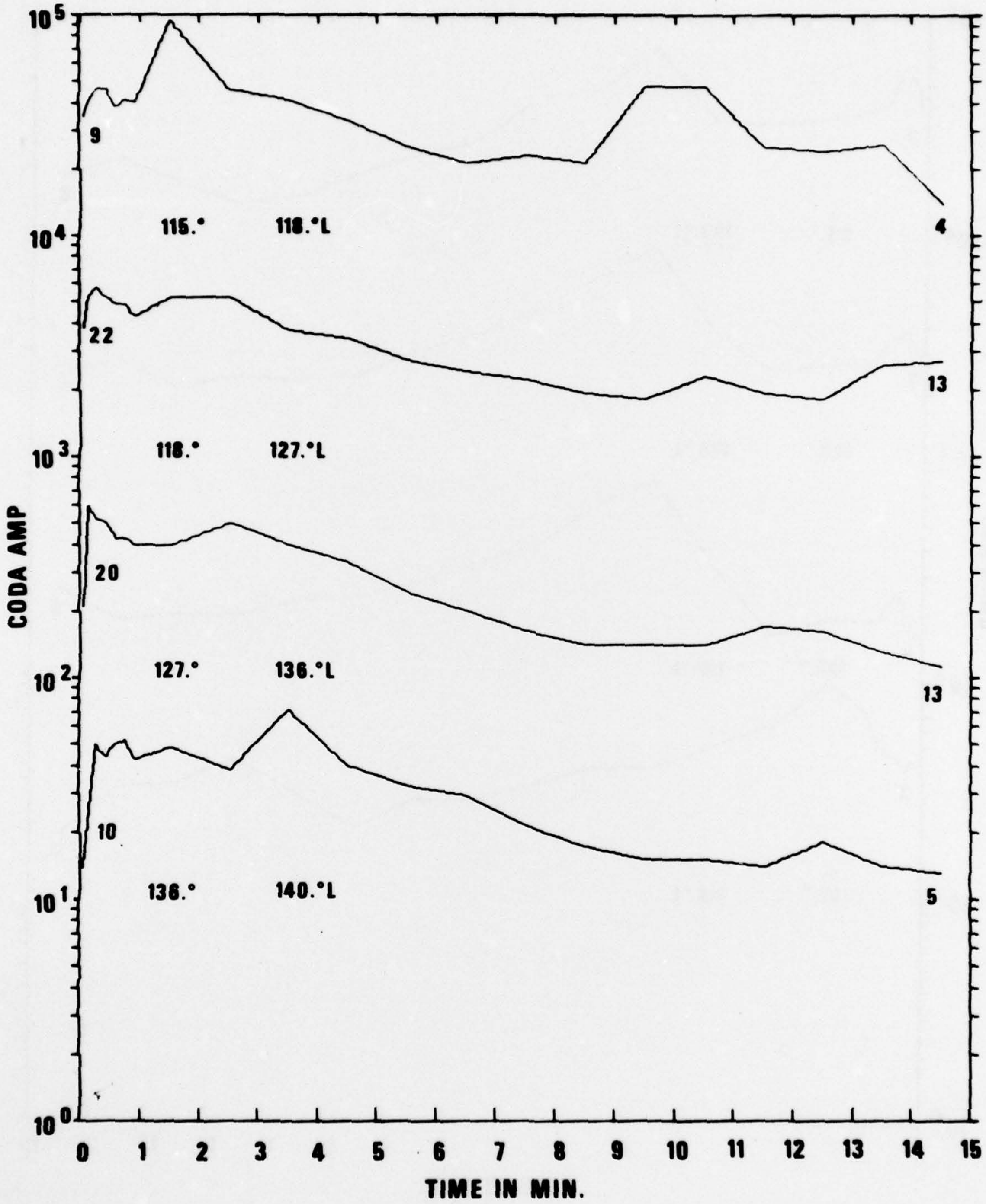
CODA AMP
TIME IN MIN.
56.° 59.°L
59.° 63.°L
63.° 67.°L
67.° 72.°L
1964 ALASKAN, VAL (62.5°)
m_b (5 sec.) = 6.7
m_b (max.) = 7.6
1964 ALASKAN
GUA (67.3°) m_b (5 sec.) = 6.9, m_b (max.) = 8.0
ANP (68.6°) m_b (5 sec.) = 6.9, m_b (max.) = 7.9



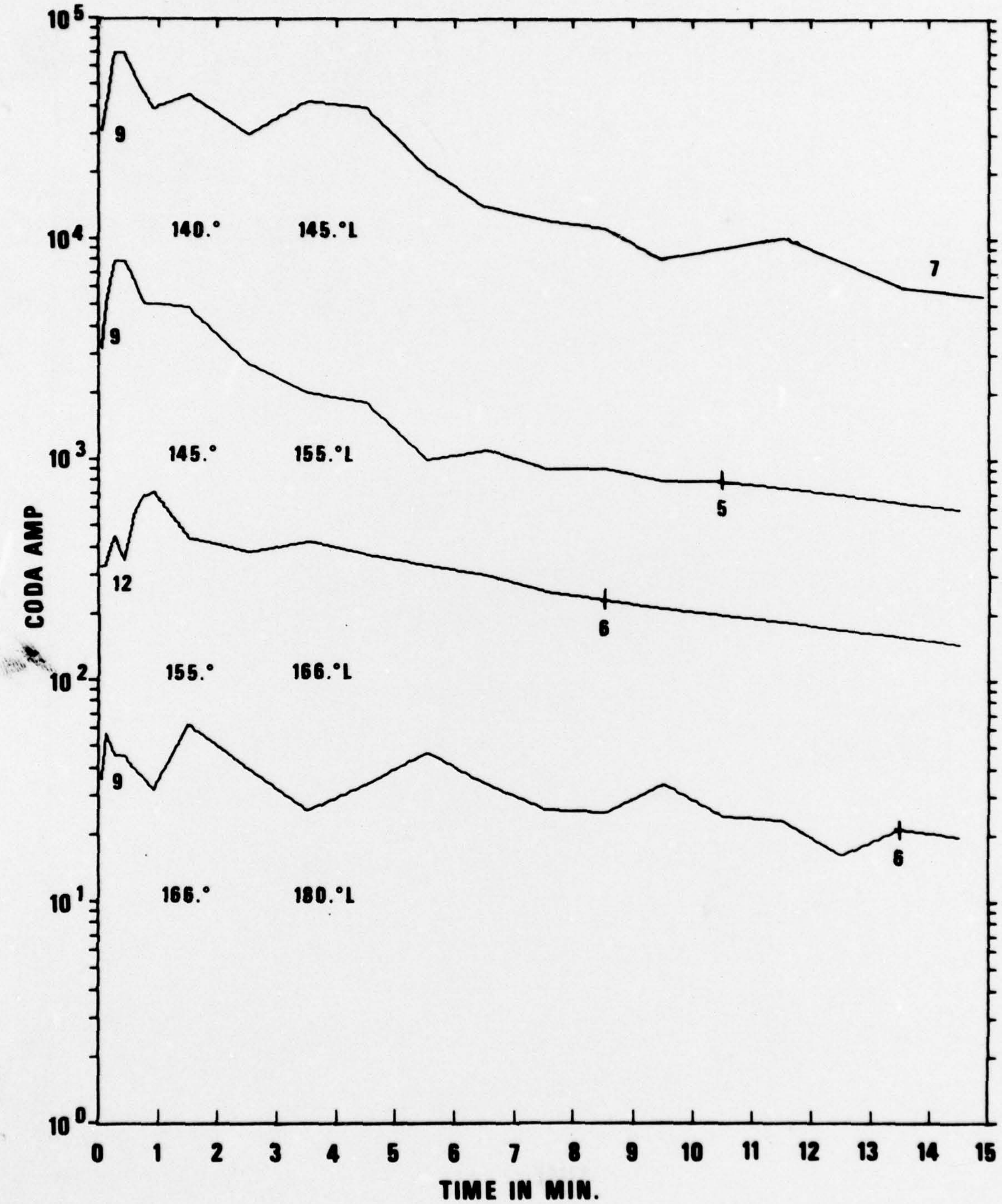
1964 ALASKAN
HKC (74.5°) m_b (5 sec.) = 6.3,
m_b (max.) = 7.0
1964 ALASKAN
ATU
72.°
79.°L
79.°
84.°L
84.°
91.°L
91.°
98.°L
13
9
5
3
16
11
17
13
CODA AMP
TIME IN MIN.



CODA AMP
TIME IN MIN.
98.°
103.°L
103.°
105.°L
105.°
110.°L
110.°
115.°L



CODA AMP
TIME IN MIN.
9
115.°
118.°L
4
22
13
118.°
127.°L
20
127.°
136.°L
13
10
136.°
140.°L
5



CODA AMP
TIME IN MIN.
140.° 145.°L
145.° 155.°L
155.° 166.°L
166.° 180.°L